IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

3SHAPE A/S,	)	
	)	
Plaintiff,	)	
	)	
v.	)	C.A. No. 18-886-LPS
	)	
ALIGN TECHNOLOGY, INC.,	)	**CONSOLIDATED**
	)	
Defendant.	)	**JURY TRIAL DEMANDED**

FIRST AMENDED ANSWER, AFFIRMATIVE DEFENSES, AND COUNTERCLAIMS OF ALIGN TECHNOLOGY, INC.

Defendant Align Technology, Inc. ("Align") hereby demands a trial by jury on all issues so triable, answers Plaintiff 3Shape A/S ("3Shape" or "Plaintiff") Amended Complaint (D.I. 44) in Civil Action No. 18-886-LPS, and presents affirmative defenses and counterclaims, as follows:

PARTIES

1. Plaintiff 3Shape is a Danish corporation with a principal place of business at Holmens Kanal 7, 1060 Copenhagen K, Denmark.

ANSWER: Align admits on information and belief that 3Shape A/S is a Danish corporation with a principal place of business at Holmens Kanal 7, 1060 Copenhagen K, Denmark.

2. Plaintiff is the owner by assignment of the entire right, title and interest in and to U.S. Patent No. 9,629,551 ("the '551 patent") entitled, "Detection of a Movable Object When 3D Scanning a Rigid Object," a copy of which is attached hereto as Exhibit A.

ANSWER: Align admits that U.S. Patent No. 9,629,551 is entitled "Detection of a Movable Object When 3D Scanning a Rigid Object." Align denies the remainder of the allegations in this paragraph.

3. Plaintiff is the owner by assignment of the entire right, title and interest in and to U.S. Patent No. 10,349,042 ("the '042 patent") entitled "Focus Scanning Apparatus," a copy of which is attached hereto as Exhibit F.

ANSWER: Align admits that U.S. Patent No. 10,349,042 is entitled "Focus Scanning Apparatus" and that a copy is attached hereto as Exhibit F. Align denies the remainder of the allegations in this paragraph.

4. Plaintiff sells an industry-leading intraoral scanner under the name TRIOS®.

ANSWER: Align admits on information and belief that 3Shape sells intraoral scanners under the name TRIOS®. Align denies the remaining allegations of this paragraph.

5. The TRIOS® system incorporates embodiments of the patented technologies of the '551 patent.

ANSWER: Denied.

6. Defendant is a competitor of Plaintiff in the field of intraoral scanners.

ANSWER: Align admits that it is a competitor of 3Shape in the field of intraoral scanners.

7. Upon information and belief, Defendant is a United States corporation organized and existing under the laws of Delaware, with a principal place of business at 2820 Orchard Parkway, San Jose, California 95134.

ANSWER: Align admits that it is a United States corporation organized and existing under the laws of Delaware, with a principal place of business at 2820 Orchard Parkway, San Jose, California 95134.

8. Upon information and belief, Defendant makes, uses, sells and offers for sale in the United States and/or imports into the United States products called "iTero Element Scanner,"

"iTero Element 2 Scanner" and "iTero Element Flex Scanner" (collectively "the iTero Element Scanners"), which comprise a handheld intraoral 3D scanner/wand.

ANSWER: Align admits it makes, uses, sells and offers for sale in the United States and/or imports into the United States products called "iTero Element Scanner," "iTero Element 2 Scanner" and "iTero Element Flex Scanner" (collectively "the iTero Element Scanners"). Align denies the remainder of the allegations in this paragraph.

JURISDICTION AND VENUE

9. This is an action for patent infringement arising under the patent laws of the United States, Title 35, United States Code, § 100 *et seq.*

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent any response is required, Align admits that Plaintiff purports to bring this action under the patent laws of the United States, pursuant to Title 35 of the United States Code. To the extent there are any remaining allegations in this paragraph not addressed by the foregoing, Align denies them.

10. This Court has subject matter jurisdiction over this action pursuant to 28 U.S.C. §§ 1331 and 1338(a).

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent any response is required, Align admits that this Court has subject matter jurisdiction over actions arising under 28 U.S.C. §§ 1331 and 1338(a). To the extent there are any remaining allegations in this paragraph, Align denies them.

11. This Court has personal jurisdiction over Defendant because it has, directly or through its agents and/or intermediaries, committed acts within Delaware giving rise to this action and/or Defendant has established minimum contacts with Delaware such that the exercise of jurisdiction would not offend traditional notions of fair play and substantial justice.

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent any response is required, Align is not contesting jurisdiction or venue in the United States District Court for the District of Delaware for the limited purposes of this civil action only. To the extent there are any remaining allegations in this paragraph not addressed by the foregoing, Align denies them.

12. Upon information and belief, Defendant regularly conducts business in Delaware, and purposefully avails itself of the privileges of conducting business in Delaware. In particular, upon information and belief, Defendant and/or its agents and/or intermediaries, make, use, import, offer for sale, sell and/or advertise their products and affiliated services in Delaware, including the iTero Element Scanners, sufficient to give rise to jurisdiction.

ANSWER: Align admits that it and/or its agents and/or intermediaries, make, use, import, offer for sale, sell and/or advertise Align products in Delaware. Align denies the remaining allegations in this paragraph.

13. Defendant has also purposely availed itself of the courts of this venue, having brought actions against Plaintiff in the federal courts of the District of Delaware, including the pending 17-cv-1646, -1647, -1648, and -1649 actions. The use of the courts of this jurisdiction is sufficient to give rise to jurisdiction over Defendant.

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent that any response is required, Align admits that it has brought the pending 17-cv-1646, -1647, -1648, and -1649 actions against 3Shape A/S in the District of Delaware. Align admits that venue in this Court is proper for the purposes of this action. To the extent there are any remaining allegations in this paragraph, Align denies them.

14. Upon information and belief, and as further described herein, Defendant has infringed and continues to infringe and/or contributorily infringe the ’551 patent and the ’042 patent in Delaware, which has led to foreseeable harm and injury to Plaintiff. Upon information and belief, Defendant derives substantial revenue from the sale of infringing products distributed within Delaware and/or expects or should reasonably expect its actions to have consequences in Delaware. In addition, upon information and belief, Defendant knowingly induces, and continues to knowingly induce, infringement of the ’551 patent and the ’042 patent within Delaware by offering for sale, selling, and/or contracting with others to market infringing products with the intent to facilitate infringing use of the products by others within Delaware and by creating and/or disseminating product information and other materials providing instruction for infringing use.

ANSWER: Denied.

15. Venue is proper in this District pursuant to 28 U.S.C. § 1391(b), (c) and/or (d), and 28 U.S.C. § 1400(b).

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent that any response is required, Align admits that venue in this Court is proper for purposes of this action. To the extent there are any remaining allegations in this paragraph, Align denies them.

COUNT 1: DIRECT INFRINGEMENT OF THE ’551 PATENT

16. Plaintiff incorporates by reference the preceding paragraphs as if set forth fully herein.

ANSWER: Align restates and reincorporates its responses to the preceding paragraphs as if fully set forth herein.

17. This cause of action arises under the patent laws of the United States, and in particular, 35 U.S.C. §§ 271, *et seq.*

<u>ANSWER</u>: This paragraph contains legal conclusions to which no response is required. To the extent any response is required, Align admits that Plaintiff purports to bring this action under the patent laws of the United States, including 35 U.S.C. § 271, *et seq*. To the extent there are any remaining allegations in this paragraph, Align denies them.

18. The ’551 patent was duly and lawfully issued by the United States Patent and Trademark Office (“USPTO”) on April 25, 2017, to listed inventors Rune Fisker, Michael Vinther, and Henrik Öjelund.

<u>ANSWER</u>: Align admits that on April 25, 2017, the United States Patent and Trademark Office issued U.S. Patent No. 9,629,551 (“the ’551 patent”), naming Rune Fisker, Michael Vinter, and Henrik Öjelund as the inventors. To the extent there are any remaining allegations in this paragraph, Align denies them.

19. Plaintiff is the owner by assignment of all right, title and interest in and to the ’551 patent. Evidence of the assignment of the ’551 patent to Plaintiff is recorded with the USPTO at Reel/Frame 043981/0005. Plaintiff is listed on the face of the ’551 patent as assignee.

<u>ANSWER</u>: Align admits that 3Shape A/S is listed on the face of the ’551 patent as assignee and an assignment recordation with the USPTO appears at Reel/Frame 043981/0005. Align denies the remaining allegations of this paragraph.

20. The ’551 patent is entitled, “Detection of a Movable Object When 3D Scanning a Rigid Object.”

<u>ANSWER</u>: Align admits that the ’551 patent is entitled “Detection of a Movable Object When 3D Scanning a Rigid Object.”

21. The ’551 patent is directed to the detection of a movable object in a location, when scanning a rigid object in the location by means of a 3D scanner for generating a virtual 3D model of the rigid object.

ANSWER: Denied.

22. Defendant makes, uses, offers to sell, sells, imports, promotes and/or demonstrates versions of its iTero Element Scanners, including the wand, cart, and/or related software, and other related products (“Accused Products”) in the United States.

ANSWER: Align admits that it makes, uses, offers to sell, sells, imports, promotes and/or demonstrates versions of its iTero Element Scanners, including the wand and cart, in the United States. To the extent this allegations concerns “related software [] and other related products”, such software and products are unidentified and Align therefore denies this allegation with respect to the same.

23. Defendant possesses knowledge of, and is aware of, the ’551 patent.

ANSWER: Admitted.

24. Defendant had previously unsuccessfully challenged the patentability of claims 1-25 of the ’551 patent in *inter partes* review (IPR) proceedings IPR2018-00195 and IPR2018-00196 before the USPTO.

ANSWER: Align admits that it petitioned for *inter partes* review proceedings IPR2018-00195 and IPR2018-00196 and that the USPTO did not institute review in response to either petition. Align denies the remaining allegations of this paragraph.

25. A panel of Administrative Patent Judges at the Patent Trial and Appeals Board of the USPTO determined that Defendant’s IPR Petitions did not present a *prima facie* case for the

unpatentability of the claims of the ’551 patent and that trial should not be instituted in connection with either Petition.

ANSWER: Align admits that it petitioned for *inter partes* review proceedings IPR2018-00195 and IPR2018-00196, and the USPTO found that “[a]pplying the standard set forth in 35 U.S.C. § 314(a), which requires demonstration of a reasonable likelihood that Petitioner would prevail with respect to at least one challenged claim, we deny Petitioner’s request and do not institute *inter partes* review of any challenged claim” in both proceedings. Decision Denying Institution of *Inter Partes* Review, IPR2018-00195; Decision Denying Institution of *Inter Partes* Review, IPR2018-00196. To the extent there are any remaining allegations in this paragraph, Align denies them.

26. Defendant has been and is now directly infringing, literally and/or under the doctrine of equivalents at least claims 1, 22, 23, and 25 of the ’551 patent.

ANSWER: Denied.

27. Each of Defendant’s Accused Products includes a system and/or a method for [1] detecting a movable object in a location, when [2] scanning a rigid object in the location by means of [3] a 3D scanner for [4] generating a virtual 3D model of the rigid object.

ANSWER: Denied.

28. Defendant’s Accused Products detect movable objects in a location.

ANSWER: Denied.

29. For example, Defendant’s Accused Products “eliminate extra process steps during intraoral scanning because iTero Element is designed to automate those for you.” *See, e.g.*, 2015 Align Technology, Inc. Brochure For General Practitioners M20324 Rev. A (“Brochure”) at 4, attached hereto as Exhibit B and entitled, “iTero® elementTM PRECISION.” Defendant’s

Brochure further states that "while you are scanning, iTero Element is engineered to simultaneously process the scan. It automatically stitches together images for rendering in the correct order, adapts to changes in positioning, and ***detects and removes soft tissues*** [*i.e.*, movable objects]. Capture everything. And view exactly what you need to see." *Id* (emphasis added).

ANSWER: Align admits that Exhibit B states "eliminate extra process steps during intraoral scanning because iTero Element is designed to automate those for you" and "while you are scanning, iTero Element is engineered to simultaneously process the scan. It automatically stitches together images for rendering in the correct order, adapts to changes in positioning and detects and removes soft tissue. Capture everything. And view exactly what you need to see." Align denies the remaining allegations in this paragraph.

30. Defendant's Accused Products scan rigid objects in the location.

ANSWER: Denied.

31. For example, Defendant's Accused Products make use of color scanning "to immediately distinguish between gingival and tooth structures [*i.e.*, rigid objects] ...." *See* Brochure at 4.

ANSWER: Align admits that Exhibit B states "to immediately distinguish between gingival and tooth structures . . . ." Align denies the remaining allegations in this paragraph.

32. Defendant's Accused Products make use of a 3D scanner.

ANSWER: Denied.

33. For example, Defendant's Accused Products include "[t]he iTero Element Intraoral Scanner ... designed to deliver speed, reliability, intuitive operations, and outstanding visualization capabilities." *See e.g.*, Brochure at 3. Further, Defendant's Accused Products include "[i]ndustry-leading, open-choice imaging [that] lets you view images in 3D." *Id.* Furthermore, Defendant's

Accused Products include "[i]ntegrated gyro technology [that] lets you rotate models on screen." *Id.* Defendant's Accused Products allows users to "[s]pin, pinch zoom and process images with a touch." *Id.*

ANSWER: Align admits that Exhibit B states "[t]he iTero Element Intraoral Scanner" and "iTero Element is designed to deliver speed, reliability, intuitive operations, and outstanding visualization capabilities." Align also admits that Exhibit B states that "[i]ntegrated gyro technology lets you rotate models on screen" and "[s]pin, pinch zoom, and process images with a touch." Align denies the remaining allegations in this paragraph.

34. Defendant's Accused Products generate virtual 3D models of rigid objects in the location.

ANSWER: Denied.

35. For example, Defendant's Accused Products' "[i]ndustry-leading, open-choice imaging lets you view images in 3D." *Id.*

ANSWER: Align admits that Exhibit B states "[i]ndustry-leading, open-choice imaging lets you view images in 3D." Align denies the remaining allegations in this paragraph.

36. Upon information and belief, each of Defendant's Accused Products makes use of a method, wherein the method comprises: [5] providing a first 3D representation of at least part of a surface by scanning at least part of the location; [6] providing a second 3D representation of at least part of the surface by scanning at least part of the location; [7] determining for the first 3D representation a first excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation, and/or determining for the second 3D representation a second excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation; [8] if a portion of the surface in the first 3D

representation is located in space in the second excluded volume, the portion of the surface in the first 3D representation is disregarded in the generation of the virtual 3D model; and/or if a portion of the surface in the second 3D representation is located in space in the first excluded volume, the portion of the surface in the second 3D representation is disregarded in the generation of the virtual 3D model.

ANSWER: Denied.

37. Defendant's Accused Products provide multiple (*i.e.*, first and second) overlapping 3D representations of a part of a surface in a short amount of time.

ANSWER: Denied.

38. For example, Defendant's Accused Products are "engineered to capture 6,000 frames per second." *See* Brochure at 3. "With a scan capture time of 40-50 milliseconds, iTero Element is designed to capture 20 scans per second." *Id.*

ANSWER: Align admits that Exhibit B states "engineered to capture 6,000 frames per second" and "[w]ith a scan capture time of 40-50 milliseconds, iTero Element is designed to capture 20 scans per second . . . ." Align denies the remaining allegations in this paragraph.

39. Further, two or more overlapping 3D representations of a part of a surface are required for Defendant's Accused Products to "stitch[] together images for rendering in the correct order." *Id.* at 4.

ANSWER: Align admits that Exhibit B states "stitches together images for rendering in the correct order . . . ." Align denies the remaining allegations in this paragraph.

40. Defendant's Accused Products determine for each 3D representation an excluded volume in space where no space can be present in both a first 3D representation and a second 3D representation.

ANSWER: Denied.

41. Each of Defendant's Accused Products rely on parallel confocal sampling, a type of digital scanning technology available to the dental scanning industry that would necessarily calculate excluded volume data which is defined by at least the distances from the scanner to the tooth surface for each successive overlapping scan. *See, e.g.*, Brochure at 2; *see also* '551 patent at 28:9-16.

ANSWER: Denied.

42. Upon information and belief, Defendant's Accused Products provide successive scans that include substantially the same location/space because each of the iTero Element Scanners has "a scan capture time of 40-50 milliseconds [and] is designed to capture 20 scans per second." *Id.* at 3.

ANSWER: Align admits that Exhibit B states "a scan capture time of 40-50 milliseconds" and "designed to capture 20 scans per second . . . ." Align denies the remaining allegations in this paragraph.

43. Defendant's Accused Products disregard portions of the surface in a first 3D representation that is located in the space of a second excluded volume in the generation of the virtual 3D model and/or disregard portions of the surface in a second 3D representation that are located in the space of a first excluded volume in the generation of a virtual 3D model.

ANSWER: Denied.

44. For example, Defendant's Accused Products were known to detect and remove soft tissue [*i.e.*, movable objects] by disregarding portions of the surface in a first 3D representation that were located in the space in a second excluded volume in the generation of the virtual 3D model and/or by disregarding portions of the surface in a second 3D representation that were

located in the space in a first excluded volume in the generation of the virtual 3D model. *See* Brochure at 4.

ANSWER: Denied.

45. Additionally, a Gardner Orthodontics Video ("Video 1") found at https://www.youtube.com/watch?v=bxZzzJvB4OM and published on December 29, 2016 (last visited June 3, 2018), attached hereto as Exhibit C, depicts Defendant's Accused Products scanning teeth (*e.g.*, a rigid object) in a location (*e.g.*, patient's mouth) by means of a 3D scanner and generating a virtual 3D model of the rigid object.

ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=bxZzzJvB4OM purports to be published by Gardner Orthodontics on December 29, 2016, and shows an iTero Element scanner. Align denies the remaining allegations in this paragraph.

46. At time 1:50 [min:sec] of Video 1, a movable object (*i.e.*, lip) is detected on the labial side of the patient's anterior teeth by Defendant's Accused Products, as depicted below.

ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=bxZzzJvB4OM shows the excerpted image (not including the callout) at time 2:03. Align denies the remaining allegations in this paragraph.

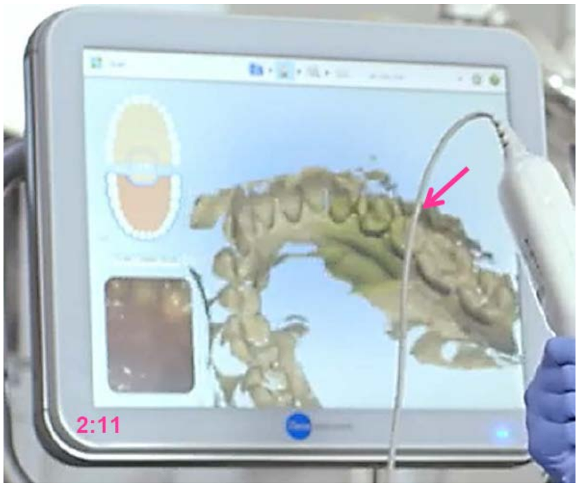
47. At time 2:03 of Video 1, surfaces associated with the movable object (*i.e.*, lip) are disregarded in the generation of the virtual 3D model of the patient's mouth as depicted below.

ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=bxZzzJvB4OM shows the excerpted image (not including the callout) at time 2:03. Align denies the remaining allegations in this paragraph

48. Further, an Align Technology, Inc. Video ("Video 2") found at https://www.youtube.com/watch?v=hDzBjbqD-KI and published on August 14, 2015 (last visited June 3, 2018), attached hereto as Exhibit D, depicts Defendant's Accused Products scanning teeth (*e.g.*, a rigid object) in a location (*e.g.*, patient's mouth) by means of a 3D scanner and generating a virtual 3D model of the rigid object.

ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=hDzBjbqD-KI purports to be published by iTero Scanner on August 14, 2015, and shows an iTero Element scanner. Align denies the remaining allegations in this paragraph.

49. As depicted below, at time 2:11 of Video 2, a movable object is detected by Defendant's Accused Products; and at time 2:12 of Video 2, surfaces associated with the movable object are disregarded in the generation of the virtual 3D model of the patient's mouth.



ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=hDzBjbqD-KI shows the excerpted images (minus the annotations) at times 2:11 and 2:12 respectively. Align denies the remaining allegations in this paragraph.

50. Further, as depicted below, at time 2:20 of Video 2, a movable object is detected by Defendant's Accused Products; and at time 2:21 of Video 2, surfaces associated with the movable object are disregarded in the generation of the virtual 3D model of the patient's mouth.

ANSWER: Align admits that the video available at https://www.youtube.com/watch?v=hDzBjbqD-KI shows the excerpted images (minus the annotations) at times 2:20 and 2:21 respectively. Align denies the remaining allegations in this paragraph.

51. Each of Defendant's Accused Products includes a system comprising a hardware processor configured to: provide a first 3D representation of at least part of a surface by scanning at least part of the location; provide a second 3D representation of at least part of the surface by

scanning at least part of the location; determine for the first 3D representation a first excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation; determine for the second 3D representation a second excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation; disregard the portion of the surface in the first 3D representation in the generation of the virtual 3D model, if a portion of the surface in the first 3D representation is located in space in the second excluded volume, and/or disregard the portion of the surface in the second 3D representation in the generation of the virtual 3D model, if a portion of the surface in the second 3D representation is located in space in the first excluded volume.

ANSWER: Denied.

52. For example, Defendant's Accused Products include a hardware processor such that "while you are scanning, iTero Element is engineered to simultaneously process the scan. It automatically stitches together images for rendering in the correct order, adapts to changes in positioning, and detects and removes soft tissue." *See, e.g.*, Brochure at 4.

ANSWER: Align admits that Exhibit B states "while you are scanning, iTero Element is engineered to simultaneously process the scan. It automatically stitches together images for rendering in the correct order, adapts to changes in positioning, and detects and removes soft tissue." Align denies the remaining allegations in this paragraph.

53. Each of Defendant's Accused Products includes a nontransitory computer readable medium encoded with a computer program product comprising program code for causing a data processing system to detect a movable object in a location, when scanning a rigid object in the location by means of a 3D scanner for generating a virtual 3D model of the rigid object by providing a first 3D representation of at least part of a surface by scanning at least part of the

location; providing a second 3D representation of at least part of the surface by scanning at least part of the location; determining for the first 3D representation a first excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation; determining for the second 3D representation a second excluded volume in space where no surface can be present in both the first 3D representation and the second 3D representation; if a portion of the surface in the first 3D representation is located in space in the second excluded volume, the portion of the surface in the first 3D representation is disregarded in the generation of the virtual 3D model; and/or if a portion of the surface in the second 3D representation is located in space in the first excluded volume, the portion of the surface in the second 3D representation the portion of the surface in when said program code is executed on the data processing system.

ANSWER: Denied.

54. For example, Defendant's Accused Products include "software [*i.e.*, a computer program product comprising program code that] automatically detects and repositions scanning start and stop points when you move to a new scanning position within the scanned segment." Brochure at 4.

ANSWER: Align admits that Exhibit B states "software automatically detects and repositions scanning start and stop points when you move to a new scanning position within the scanned segment." Align denies the remaining allegations in this paragraph.

55. Further, Defendant's Accused Products include a computer program product comprising program code that "automatically stitches together images for rendering in the correct order, adapts to changes in positioning, and detects and removes soft tissue." *Id.*

ANSWER: Align admits that Exhibit B states "automatically stitches together images for rendering in the correct order, adapts to changes in positioning, and detects and removes soft tissue." Align denies the remaining allegations in this paragraph.

56. On information and belief, Defendant's Accused Products rely on a system hard disk, *i.e.*, a nontransitory computer readable medium encoded with the software discussed in paragraphs 54 and 55 to carry out the claimed methods of the '551 patent. Defendant's Accused Products also "automatically save scan data every two seconds and save it to the system's hard disk." *Id.*

ANSWER: Align admits that Exhibit B states "automatically save scan data every two seconds and save it to the system's hard disk." Align denies the remaining allegations in this paragraph.

57. These features of each of Defendant's Accused Products in paragraphs 26-56 above correspond to those recited and claimed in at least claims 1, 22, 23, and 25 of the '551 patent.

ANSWER: Denied.

58. Defendant has sold and/or offered for sale its iTero Element Scanners in the United States at trade shows in Chicago, IL, New York, NY and Detroit, MI. The "Align Technology Announces Next Generation iTero(R) Element(TM) Intraoral Scanner" webpage (last visited May 4, 2018), attached hereto as Exhibit E, is further evidence of Defendant's sale and/or offer for sale of the iTero Element Scanner product in the United States.

ANSWER: Align admits that it has sold and/or offered for sale its iTero Element Scanner in the United States at trade shows in Chicago, IL, New York, NY and Detroit, MI. Align denies the remaining allegations in this paragraph.

59. Defendant thus directly infringes, literally and/or under the doctrine of equivalents, and/or indirectly infringes, at least claims 1, 22, 23, and 25 of the '551 patent.

ANSWER: Denied.

60. On information and belief, Defendant intends to, and continues to intend to, directly infringe the ’551 patent through the sale of the Accused Products.

ANSWER: Denied.

61. Defendant knew or should have known of the ’551 patent and its infringement of the ’551 patent, and has acted and continues to act, in an egregious and wanton manner by infringing the ’551 patent.

ANSWER: Denied.

62. Despite knowing that its actions constituted infringement of the ’551 patent and/or despite knowing that there was a high likelihood that its actions constituted infringement of the patent, Defendant nevertheless continued its infringing actions, and continues to make, use, and sell, the Accused Products.

ANSWER: Denied.

63. Defendant’s acts of infringement have injured and damaged Plaintiff and will continue to injure and damage Plaintiff.

ANSWER: Denied.

64. Defendant’s actions have caused Plaintiff to suffer irreparable harm resulting from the loss of its lawful patent rights and the loss of its ability to exclude others from the market.

ANSWER: Denied.

65. Upon information and belief, Defendant will continue these infringing acts unless enjoined by this court.

ANSWER: Denied.

COUNT 2: INDIRECT INFRINGEMENT OF THE ’551 PATENT BY INDUCEMENT

66. Plaintiff repeats and realleges the allegations set forth in paragraphs 1 to 65 above as if fully set forth herein.

ANSWER: Align restates and reincorporates its responses to paragraphs 1-65 as if fully set forth herein.

67. Defendant is liable for inducing infringement of the ’551 patent under 35 U.S.C. §271(b) by having knowledge of the ’551 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, direct infringement of the ’551 patent, with specific intent, by its customers.

ANSWER: Denied.

68. Specifically, Defendant actively induces infringement of the ’551 patent by, *inter alia*, training its customers on the use of the Accused Products and/or promotion, sales, and/or importation of the Accused Products including the infringing iTero Element Scanners to Defendant’s customers including, but not limited to, resellers and end users for their use of the system claimed in the ’551 patent.

ANSWER: Denied.

69. Defendant’s customers for the Accused Products directly infringe the ’551 patent by making, using, selling, offering for sale, and/or importing the iTero Element Scanners.

ANSWER: Denied.

70. For example, Defendant actively induces infringement of the ’551 patent, because Defendant has knowledge that end users of Defendant’s iTero Element Scanners including, but not limited to, dentists and technicians, use Defendant’s infringing iTero Element Scanners product in the United States, and because Defendant encourages such acts resulting in direct patent infringement, by, *inter alia*, training, promotion, sales, and/or importation of the infringing iTero

Element Scanners to Defendant's customers including, but not limited to, resellers and end users for their use of the system claimed in the '551 patent.

ANSWER: Denied.

71. On information and belief, Defendant intends to, and continues to intend to, indirectly infringe the '551 patent through inducement of the sale and use of the Accused Products.

ANSWER: Denied.

72. Defendant knew or should have known of the '551 patent and has acted, and continues to act, in an egregious and wanton manner by infringing the '551 patent.

ANSWER: Denied.

73. Despite knowing that its actions constituted inducement infringement of the '551 patent and/or despite knowing that there was a high likelihood that its actions constituted inducement infringement of the patent, Defendant nevertheless continued its infringing actions, and continues to make, use, and sell, the Accused Products.

ANSWER: Denied.

74. Defendant's acts of infringement have injured and damaged Plaintiff and will continue to injure and damage Plaintiff.

ANSWER: Denied.

75. Defendant's actions have caused Plaintiff to suffer irreparable harm resulting from the loss of its lawful patent rights and the loss of its ability to exclude others from the market. Upon information and belief, Defendant will continue these infringing acts unless enjoined by this court.

ANSWER: Denied.

COUNT 3: INDIRECT INFRINGEMENT OF THE '551 PATENT BY CONTRIBUTORY INFRINGEMENT

76. Plaintiff repeats and realleges paragraphs 1 to 75 as if fully set forth herein.

ANSWER: Align restates and reincorporates its responses to paragraphs 1-75 as if fully set forth herein.

77. Defendant is liable for contributory infringement of the '551 patent under 35 U.S.C. §271(c) by having sold or offered to sell, and continuing to sell or offer for sale the iTero Element Scanners within the United States and/or by importing the iTero Element Scanners into the United States because the iTero Element Scanners constitute a material part of the invention embodied in the '551 patent, which Defendant knows to be especially made and/or especially adapted for use in infringement of the '551 patent, and which is not a staple article or commodity of commerce suitable for substantial non-infringing use.

ANSWER: Denied.

78. Defendant is liable for contributory infringement by having knowledge of the '551 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, direct infringement of the '551 patent by its customers including, but not limited to, resellers and end users of the iTero Element Scanners.

ANSWER: Denied.

79. Specifically, Defendant contributes to infringement of the '551 patent by, *inter alia*, promotion, sales, and/or importation of the infringing iTero Element Scanners to Defendant's customers including, but not limited to, resellers and end users for their use of the system claimed in the '551 patent. Those customers directly infringe the '551 patent by making, using, selling, offering for sale, and/or importing the iTero Element Scanners. For example, Defendant is liable for contributory infringement by having knowledge of the '551 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, end users of Defendant's

iTero Element Scanners including, but not limited to, dentists and technicians, to directly infringe the '551 patent by using Defendant's iTero Element Scanners in the United States.

ANSWER: Denied.

80. Defendant's past and ongoing infringement of the '551 patent has and will continue to irreparably harm Plaintiff.

ANSWER: Denied.

81. Defendant's past and ongoing infringement of the '551 patent has and will continue to cause Plaintiff damages.

ANSWER: Denied.

82. Defendant's past and ongoing infringement of the '551 patent, upon information and belief, has been knowing and willful.

ANSWER: Denied.

COUNT 4: DIRECT INFRINGEMENT OF THE '042 PATENT

83. Plaintiff incorporates by reference the preceding paragraphs as if set forth fully herein.

ANSWER: Align restates and reincorporates its responses to the preceding paragraphs as if fully set forth herein.

84. This cause of action arises under the patent laws of the United States, and in particular, 35 U.S.C. §§ 271, *et seq.*

ANSWER: This paragraph contains legal conclusions to which no response is required. To the extent any response is required, Align admits that Plaintiff purports to bring this action under the patent laws of the United States, including 35 U.S.C. § 271. To the extent there are any remaining allegations in this paragraph not addressed by the foregoing, Align denies them.

85. The ’042 patent was duly and lawfully issued by the United States Patent and Trademark Office (“USPTO”) on July 9, 2019, to listed inventors Rune Fisker, Henrik Öjelund, Rasmus Kjaer, Mike van der Poel, Arish A. Qazi and Karl-Josef Hollenbeck.

ANSWER: Align admits that on July 9, 2019, the United States Patent and Trademark Office issued U.S. Patent No. 10,349,042 (“the ’042 patent”), naming Rune Fisker, Henrik Öjelund, Rasmus Kjaer, Mike van der Poel, Arish A. Qazi and Karl-Josef Hollenbeck as the inventors. To the extent there are any remaining allegations in this paragraph, Align denies them.

86. Plaintiff is the owner by assignment of all right, title and interest in and to the ’042 patent. Evidence of the assignment of the ’042 patent to Plaintiff is recorded with the USPTO at Reel/Frame 048470/0993. Plaintiff is listed on the face of the ’042 patent as assignee.

ANSWER: Align admits that 3Shape A/S is listed on the face of the ’042 patent as assignee. Align denies the remaining allegations of this paragraph.

87. The ’042 patent is entitled, “Focus Scanning Apparatus.”

ANSWER: Align admits that the ’042 patent is entitled “Focus Scanning Apparatus.”

88. The ’042 patent is directed to intraoral scanners for providing data for 3D geometry of at least a part of the surface of an object in an oral cavity, and methods of providing data for 3D geometry of at least a part of the surface of an object in an oral cavity using an intraoral scanner.

ANSWER: Denied.

89. Defendant makes, uses, offers to sell, sells, imports, promotes and/or demonstrates versions of its iTero Element Scanners, including the wand, cart, and/or related software, and other related products (“Accused Products”) in the United States.

ANSWER: Align admits that it makes, uses, offers to sell, sells, imports, promotes and/or demonstrates versions of its iTero Element Scanners, including the wand and cart, in the United

States. To the extent this allegations concerns "related software [] and other related products", such software and products are unidentified and Align therefore denies this allegation with respect to the same.

90. Defendant possesses knowledge of, and is aware of, the '042 patent.

ANSWER: Admitted.

91. Defendant has been and is now directly infringing, literally and/or under the doctrine of equivalents at least claims 1, 17, 19, and 21 of the '042 patent.

ANSWER: Denied.

92. Each of Defendant's Accused Products includes an intraoral scanner for providing data for 3D geometry of at least a part of the surface of an object in an oral cavity, and a method of providing data for 3D geometry of at least a part of the surface of an object in an oral cavity using an intraoral scanner.

ANSWER: Denied.

93. Upon information and belief, each of Defendant's iTero Element Scanners comprises a color image sensor comprising an array of sensor elements.

ANSWER: Denied.

94. Upon information and belief, each of Defendant's iTero Element Scanners comprises lighting equipment configured to generate a probe light.

ANSWER: Denied.

95. Upon information and belief, each of Defendant's iTero Element Scanners comprises an optical system comprising a beam splitter, at least one lens, and a tip configured to be inserted into the oral cavity.

ANSWER: Denied.

96. Upon information and belief, in each of Defendant's iTero Element Scanners, the intraoral scanner is configured to operate by translating a focus plane along an optical axis of the optical system to capture one or more 2D images.

ANSWER: Denied.

97. Upon information and belief, in each of Defendant's iTero Element Scanners, the lens is configured such that the intraoral scanner transmits a part of the probe light from the lighting equipment through the optical system and towards the object such that the part of the probe light is focused onto at least two different parts of the object, wherein the part of the probe light as focused on a first part of the object is defined by a first divergence angle in relation to a first propagation axis, wherein the part of the probe light as focused on a second part of the object is defined by a second divergence angle in relation to a second propagation axis, and the first propagation axis and the second propagation axis are non-parallel.

ANSWER: Denied.

98. Upon information and belief, in each of Defendant's iTero Element Scanners, reflected light results from the part of the probe light being reflected from the part of the surface of the object.

ANSWER: Denied.

99. Upon information and belief, in each of Defendant's iTero Element Scanners, the intraoral scanner is further configured to transmit the reflected light from the part of the surface of the object back through the optical system such that the reflected light is focused on the color image sensor, the color image sensor being configured to produce the data for the 3D geometry from a series of 2D images captured by the intraoral scanner translating the focus plane along the

optical axis of the optical system, at least one of the series of 2D images being generated using the reflected light focused on the color image sensor.

ANSWER: Denied.

100. These features of each of the iTero Element Scanners in paragraphs 93 to 99 above correspond to those recited and claimed in at least claim 1 of the ’042 patent.

ANSWER: Denied.

101. Upon information and belief, in each of Defendant’s iTero Element Scanners, the lens is configured such that the intraoral scanner transmits at least a part of the probe light from the lighting equipment through the optical system and towards the object such that the part of the probe light is non-telecentrically focused on a part of the surface of the object.

ANSWER: Denied.

102. These features of each of the iTero Element Scanners in paragraph 101 above correspond to those recited and claimed in at least claim 17 of the ’042 patent.

ANSWER: Denied.

103. Upon information and belief, in each of Defendant’s iTero Element Scanners, the lens is configured such that the intraoral scanner transmits at least a part of the probe light from the lighting equipment through the optical system and towards the object such that the part of the probe light is focused onto at least two different parts of the object, wherein the part of the probe light as focused on a first part of the object is defined by a first divergence angle in relation to a first propagation axis, wherein the part of the probe light as focused on a second part of the object is defined by a second divergence angle in relation to a second propagation axis, and the first propagation axis diverges from the second propagation axis.

ANSWER: Denied.

104. These features of each of the iTero Element Scanners in paragraph 103 above correspond to those recited and claimed in at least claim 21 of the '042 patent.

ANSWER: Denied.

105. Upon information and belief, operation of each of Defendant's iTero Element Scanners comprises inserting the tip into the oral cavity.

ANSWER: Denied.

106. Upon information and belief, operation of each of Defendant's iTero Element Scanners comprises generating a probe light using the lighting equipment.

ANSWER: Denied.

107. Upon information and belief, operation of each of Defendant's iTero Element Scanners comprises transmitting at least a part of the probe light from the lighting equipment through the optical system and towards the object such that the part of the probe light is non-telecentrically focused on at least a part of the surface of the object.

ANSWER: Denied.

108. Upon information and belief, operation of each of Defendant's iTero Element Scanners comprises reflecting the part of the probe light from the part of the surface of the object to produce reflected light.

ANSWER: Denied.

109. Upon information and belief, operation of each of Defendant's iTero Element Scanners comprises transmitting the reflected light from the part of the surface of the object back through the optical system such that the reflected light is focused on the color image sensor, the color image sensor producing the data for the 3D geometry from a series of 2D images captured by the intraoral scanner translating a focus plane along an optical axis of the optical system, at

least one of the series of 2D images being generated using the reflected light focused on the color image sensor.

ANSWER: Denied.

110. These features of each of the iTero Element Scanners in paragraphs 105-109 above correspond to those recited and claimed in at least claim 19 of the '042 patent.

ANSWER: Denied.

111. For example, upon information and belief, Defendant describes its iTero Element Scanner on an online webpage entitled "Products | iTero Intraoral Scanner," a copy of which is attached hereto as Exhibit G. The webpage contains text and an image describing and showing the iTero Element Scanner, and that it embodies the focus scanner recited in at least claims 1, 17, 19 and 21 of the '042 patent. *See* Products | iTero Intraoral Scanner (2016), http://www.itero.com/en-us/products/itero_element (last visited June 20, 2019) (the "Products | iTero Intraoral Scanner" webpage). The "Products | iTero Intraoral Scanner" webpage illustrates that a focus scanner comprises a color image sensor comprising an array of sensor elements, as recited in claims 1, 17, 19 and 21 of the '042 patent. *See* the "Products | iTero Intraoral Scanner" webpage ("Color scanning gives you a significant leap forward in visualization. The color sensor is integrated in the iTero Element scanner, and the patented dual-aperture lens system is designed to simultaneously capture 2D images in color with highly accurate 3D laser scanning.").

ANSWER: Align admits that the webpage states "[c]olor scanning gives you a significant leap forward in visualization. The color sensor is integrated in the iTero Element scanner, and the patented dual-aperture lens system is designed to simultaneously capture 2D iamges in color with highly accurate 3D laser scanning." Align denies the remaining allegations in this paragraph.

112. In addition, upon information and belief, Defendant illustrated the "Products | iTero Intraoral Scanner" webpage with the following image:

ANSWER: Align admits that the webpage includes the excerpted image. To the extent there are any remaining allegations in this paragraph not addressed by the foregoing, Align denies them.

113. The image shows that the iTero Element Scanner comprises a tip configured to be inserted into the oral cavity, and reflecting light off of an object in the oral cavity.

ANSWER: Denied.

114. In addition, upon information and belief, Defendant describes its iTero Element Scanner on an online webpage entitled "iTero intraoral scanners," a copy of which is attached hereto as Exhibit H. The webpage contains text and images describing and showing the iTero Element Scanner and that it embodies the focus scanner recited in at least claims 1, 17, 19 and 21 of the '042 patent. *See* Align Technology (2019). http://www.aligntech.com/solutions/itero_scanner (last visited June 20, 2019) (the "iTero intraoral scanners" webpage). The "iTero intraoral scanners" webpage illustrates that a focus scanner comprises lighting equipment configured to generate a probe light, wherein the intraoral scanner is configured to operate by translating a focus plane along an optical axis of the optical system to

capture one or more 2D images, and wherein the intraoral scanner is further configured to transmit the reflected light from the part of the surface of the object back through the optical system such that the reflected light is focused on the color image sensor, the color image sensor being configured to produce the data for the 3D geometry from a series of 2D images captured by the intraoral scanner translating the focus plane along the optical axis of the optical system, at least one of the series of 2D images being generated using reflected light focused on the color image sensor, as recited in at least claims 1, 17 and 21 of the '042 patent. *See* the "iTero intraoral scanners" webpage ("The iTero Element intraoral scanner . . . . [i]ts parallel confocal imaging technology uses optical and laser scanning to achieve accurate scans in color.").

ANSWER: Align admits that the webpage states "The iTero Element intraoral scanner" and "[i]ts parallel confocal imaging technology uses optical and laser scanning to achieve accurate scans in color." Align denies the remaining allegations in this paragraph.

115. Upon information and belief, each of Defendant's iTero Element Scanners is configured such that the part of the probe light is focused onto at least two different parts of the object, wherein the part of the probe light as focused on a first part of the object is defined by a first divergence angle in relation to a first propagation axis, wherein the part of the probe light as focused on a second part of the object is defined by a second divergence angle in relation to a second propagation axis, and the first propagation axis and the second propagation axis are non-parallel (as recited in at least claim 1 of the '042 patent), such that at least a part of the probe light is non-telecentrically focused on at least a part of the surface of the object (as recited in at least claims 17 and 19 of the '042 patent), and such that the part of the probe light is focused onto at least two different parts of the object, wherein the part of the probe light as focused on a first part of the object is defined by a first divergence angle in relation to a first propagation axis, wherein

the part of the probe light as focused on a second part of the object is defined by a second divergence angle in relation to a second propagation axis, and the first propagation axis diverges from the second propagation axis (as recited in at least claim 21 of the '042 patent).

ANSWER: Denied.

116. Defendant has sold and/or offered for sale its iTero Element Scanners in the United States at trade shows in Chicago, IL, New York, NY and Detroit, MI. The "Align Technology Announces Next Generation iTero(R) Element(TM) Intraoral Scanner" webpage (last visited May 4, 2018), attached hereto as Exhibit E, is further evidence of Defendant's sale and/or offer for sale of the iTero Element Scanner product in the United States.

ANSWER: Align admits that it has sold and/or offered for sale its iTero Element Scanner in the United States at trade shows in Chicago, IL, New York, NY and Detroit, MI. Align denies the remaining allegations in this paragraph.

117. Defendant thus directly infringes, literally and/or under the doctrine of equivalents, and/or indirectly infringes, at least claims 1, 17, 19 and 21 of the '042 patent.

ANSWER: Denied.

118. On information and belief, Defendant intends to, and continues to intend to, directly infringe the '042 patent through the sale of the Accused Products.

ANSWER: Denied.

119. Defendant knew or should have known of the '042 patent and its infringement of the '042 patent, and has acted and continues to act, in an egregious and wanton manner by infringing the '042 patent.

ANSWER: Denied.

120. Despite knowing that its actions constituted infringement of the ’042 patent and/or despite knowing that there was a high likelihood that its actions constituted infringement of the patent, Defendant nevertheless continued its infringing actions, and continues to make, use, and sell, the Accused Products.

ANSWER: Denied.

121. Defendant’s acts of infringement have injured and damaged Plaintiff and will continue to injure and damage Plaintiff.

ANSWER: Denied.

122. Defendant’s actions have caused Plaintiff to suffer irreparable harm resulting from the loss of its lawful patent rights and the loss of its ability to exclude others from the market.

ANSWER: Denied.

123. Upon information and belief, Defendant will continue these infringing acts unless enjoined by this court.

ANSWER: Denied.

COUNT 5: INDIRECT INFRINGEMENT OF THE ’042 PATENT BY INDUCEMENT

124. Plaintiff repeats and realleges the allegations set forth in paragraphs 1 to 123 above as if fully set forth herein.

ANSWER: Align restates and reincorporates its responses to preceding paragraphs 1 to 123 as if fully set forth herein.

125. Defendant is liable for inducing infringement of the ’042 patent under 35 U.S.C. §271(b) by having knowledge of the ’042 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, direct infringement of the ’042 patent, with specific intent, by its customers.

ANSWER: Denied.

126. Specifically, Defendant actively induces infringement of the ’042 patent by, *inter alia*, training its customers on the use of the Accused Products and/or promotion, sales, and/or importation of the Accused Products including the infringing iTero Element Scanners to Defendant’s customers including, but not limited to, resellers and end users for their use of the system claimed in the ’042 patent.

ANSWER: Denied.

127. Defendant’s customers for the Accused Products directly infringe the ’042 patent by making, using, selling, offering for sale, and/or importing the iTero Element Scanners.

ANSWER: Denied.

128. For example, Defendant actively induces infringement of the ’042 patent, because Defendant has knowledge that end users of Defendant’s iTero Element Scanners including, but not limited to, dentists and technicians, use Defendant’s infringing iTero Element Scanners product in the United States, and because Defendant encourages such acts resulting in direct patent infringement, by, *inter alia*, training, promotion, sales, and/or importation of the infringing iTero Element Scanners to Defendant’s customers including, but not limited to, resellers and end users for their use of the system claimed in the ’042 patent.

ANSWER: Denied.

129. On information and belief, Defendant intends to, and continues to intend to, indirectly infringe the ’042 patent through inducement of the sale and use of the Accused Products.

ANSWER: Denied.

130. Defendant knew or should have known of the ’042 patent and has acted, and continues to act, in an egregious and wanton manner by infringing the ’042 patent.

ANSWER: Denied.

131. Despite knowing that its actions constituted inducement infringement of the ’042 patent and/or despite knowing that there was a high likelihood that its actions constituted inducement infringement of the patent, Defendant nevertheless continued its infringing actions, and continues to make, use, and sell, the Accused Products.

ANSWER: Denied.

132. Defendant’s acts of infringement have injured and damaged Plaintiff and will continue to injure and damage Plaintiff.

ANSWER: Denied.

133. Defendant’s actions have caused Plaintiff to suffer irreparable harm resulting from the loss of its lawful patent rights and the loss of its ability to exclude others from the market. Upon information and belief, Defendant will continue these infringing acts unless enjoined by this court.

ANSWER: Denied.

COUNT 6: INDIRECT INFRINGEMENT OF THE ’042 PATENT BY CONTRIBUTORY INFRINGEMENT

134. Plaintiff repeats and realleges paragraphs 1 to 133 as if fully set forth herein.

ANSWER: Align restates and reincorporates its responses to preceding paragraphs 1 to 133 as if fully set forth herein

135. Defendant is liable for contributory infringement of the ’042 patent under 35 U.S.C. §271(c) by having sold or offered to sell, and continuing to sell or offer for sale the iTero Element Scanners within the United States and/or by importing the iTero Element Scanners into the United States because the iTero Element Scanners constitute a material part of the invention embodied in the ’042 patent, which Defendant knows to be especially made and/or especially adapted for use

in infringement of the ’042 patent, and which is not a staple article or commodity of commerce suitable for substantial non-infringing use.

ANSWER: Denied.

136. Defendant is liable for contributory infringement by having knowledge of the ’042 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, direct infringement of the ’042 patent by its customers including, but not limited to, resellers and end users of the iTero Element Scanners.

ANSWER: Denied.

137. Specifically, Defendant contributes to infringement of the ’042 patent by, *inter alia*, promotion, sales, and/or importation of the infringing iTero Element Scanners to Defendant’s customers including, but not limited to, resellers and end users for their use of the system claimed in the ’042 patent. Those customers directly infringe the ’042 patent by making, using, selling, offering for sale, and/or importing the iTero Element Scanners. For example, Defendant is liable for contributory infringement by having knowledge of the ’042 patent and knowingly causing or intending to cause, and continuing to knowingly cause or intend to cause, end users of Defendant’s iTero Element Scanners including, but not limited to, dentists and technicians, to directly infringe the ’042 patent by using Defendant’s iTero Element Scanners in the United States.

ANSWER: Denied.

138. Defendant’s past and ongoing infringement of the ’042 patent has and will continue to irreparably harm Plaintiff.

ANSWER: Denied.

139. Defendant’s past and ongoing infringement of the ’042 patent has and will continue to cause Plaintiff damages.

ANSWER: Denied.

140. Defendant's past and ongoing infringement of the '042 patent, upon information and belief, has been knowing and willful.

ANSWER: Denied.

PRAYER FOR RELIEF

Defendant denies that Plaintiff is entitled to any of the relief requested by the Complaint, or any other remedy or relief whatsoever.

AFFIRMATIVE DEFENSES

Without any admission as to burden of proof, burden of persuasion, or the truth of any of the allegations in Plaintiff's Complaint, Defendant states the following affirmative defenses. Defendant reserves the right to assert additional defenses, as warranted by the facts learned through investigation and discovery.

First Affirmative Defense
(Invalidity of U.S. Patent No. 9,629,551)

One or more claims of the '551 patent are invalid for failure to comply with one or more of the requirements for patentability set forth in Title 35 of the U.S. Code, including §§ 101, 102, 103, and 112, and/or invalid under any other ground provided by 35 U.S.C. § 282, and/or based on other judicially-created bases for invalidity.

Second Affirmative Defense
(Non-Infringement of U.S. Patent No. 9,629,551)

Plaintiff has failed to aver any facts that support its allegations of infringement by the proposed Accused Products. The Accused Products will not infringe any valid and enforceable claim of the '551 patent, either literally or under the doctrine of equivalents.

Third Affirmative Defense
(Invalidity of U.S. Patent No. 10,349,042)

One or more claims of the ’042 patent are invalid for failure to comply with one or more of the requirements for patentability set forth in Title 35 of the U.S. Code, including §§ 101, 102, 103, and 112, and/or invalid under any other ground provided by 35 U.S.C. § 282, and/or based on other judicially-created bases for invalidity.

Fourth Affirmative Defense
(Non-Infringement of U.S. Patent No. 10,349,042)

Plaintiff has failed to aver any facts that support its allegations of infringement by the proposed Accused Products. The Accused Products will not infringe any valid and enforceable claim of the ’042 patent, either literally or under the doctrine of equivalents.

Fifth Affirmative Defense
(Prosecution History Estoppel)

Plaintiff is estopped from arguing and has waived arguments that the claims of the ’551 and ’042 patents cover Align products by virtue of amendments, positions, and arguments made to the USPTO when obtaining the asserted patent.

Sixth Affirmative Defense
(Failure to State a Claim)

Plaintiff’s Complaint fails to state a claim upon which relief can be granted.

Seventh Affirmative Defense
(Lack of Standing)

Plaintiff does not have standing to assert claims for patent infringement under 35 U.S.C. § 271(a), (b), and (c).

Eighth Affirmative Defense
(Equitable Estoppel, Laches, Waiver, Acquiescence, and/or Unclean Hands)

Plaintiff's claims for relief are barred by the doctrines of waiver, laches, acquiescence, unclean hands, and/or estoppel with respect to asserted claims of the '551 and '042 patents because Plaintiff misled Align as to its intent not to enforce these patents against Align after it learned, or through reasonable diligence should have learned, of its causes of action against Align, and since such time Align has expended substantial amounts of time, money, and effort to build its business, brand and recognition of its name and products.

Ninth Affirmative Defense
(Covenant Not to Sue)

Plaintiff has covenanted not to sue Align on the asserted patents.

Tenth Affirmative Defense
(License)

Plaintiff's claims are barred with respect to the asserted claims of the '551 and '042 patents to the extent the accused Align products are expressly or impliedly licensed under these patents.

Eleventh Affirmative Defense
(Patent Misuse)

Plaintiff's claims are barred, in whole or in part, by the doctrine of patent misuse.

Twelfth Affirmative Defense
(Unavailability of Relief – Bar to Damages, Marking and Notice)

Plaintiff's claim for relief is barred, in whole or in part, because Plaintiff is not entitled to damages under 35 U.S.C. § 286, Plaintiff has failed to plead and meet the requirements of 35 U.S.C. § 287 on marking and notice, and has otherwise failed to show that it is entitled to any damages prior to the filing date of Plaintiff's Complaint for Patent Infringement.

Thirteenth Affirmative Defense
(Additional Defenses or Counterclaims)

Defendant reserves all defenses available under the Federal Rules of Civil Procedure and the U.S. Patent laws and any additional defenses or counterclaims that discovery may reveal including that Plaintiff has failed to aver any facts supporting the conclusion that it has suffered any irreparable injury or harm under 35 U.S.C. § 282, and that Plaintiff has failed to aver any facts supporting that this is an exception case and/or an award of attorney's fees under 35 U.S.C. § 285.

WHEREFORE, Defendant requests that Plaintiff's Complaint be dismissed with prejudice and that Defendant be awarded the costs of this action, its attorneys' fees, and all other relief that this Court deems just and proper.

COUNTERCLAIMS

For their counterclaims against Counterclaim-Defendant 3Shape A/S ("Counterclaim-Defendant" or "3Shape"), Counterclaim-Plaintiff Align Technology, Inc. (collectively "Counterclaim-Plaintiff" or "Align"), state as follows:

PARTIES

1. Align is a United States corporation organized and existing under the laws of Delaware, with a principal place of business at 2820 Orchard Parkway, San Jose, California 95134.

2. Upon information and belief, Counterclaim-Defendant 3Shape is a Danish corporation with a principal place of business at Holmens Kanal 7, 1060 Copenhagen K, Denmark.

JURISDICTION AND VENUE

3. Counterclaim-Plaintiff's counterclaims arise under the Patent Laws of the United States, 35 U.S.C. § *et seq.* and the Declaratory Judgment Act, 28 U.S.C. §§ 2201 and 2202.

4. This Court has original jurisdiction over the subject matter of these counterclaims pursuant to 28 U.S.C. §§ 1331, 1338, 2201, and 2202.

5. This Court has personal jurisdiction over Counterclaim-Defendant because Counterclaim-Defendant has availed itself of the rights and privileges of this forum by bringing this civil action in this judicial district and because, upon information and belief, Counterclaim-Defendant conducts substantial business in, and has regular and systematic contact with, this judicial district.

6. Further, 3Shape has, directly or through agents and/or intermediaries, committed acts within Delaware giving rise to this action and/or have established minimum contacts with Delaware such that the exercise of jurisdiction would not offend traditional notions of fair play and justice. On information and belief, 3Shape regularly conducts business in Delaware, and purposefully availed itself of the privileges of conducting business in Delaware. In particular, on information and belief, 3Shape, directly and/or through its agents and/or intermediaries, make, use, import, offer for sale, sell, and/or advertise their products and affiliated services in Delaware. 3Shape has placed, and continues to place, infringing products into the stream of commerce, via an established distribution channel, with the knowledge and/or understanding that such products are sold in the United States including in Delaware and specifically including this District.

7. On information and belief, 3Shape has derived substantial revenue from their infringing activity occurring within the State of Delaware and within this District and/or should reasonably expect their actions to have consequences in Delaware. In addition, 3Shape has

knowingly induced and continues to knowingly induced infringement within this District by advertising, marketing, offering for sale and/or selling devices containing infringing functionality within this District to at least resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users, and by providing instructions, user manuals, in person and/or online training, advertising and/or marketing materials which facilitate, direct or encourage the use of infringing functionality with knowledge thereof.

8. 3Shape has committed patent infringement in Delaware that has led to foreseeable harm and injury to Align, a Delaware corporation.

9. Additionally, 3Shape is subject to jurisdiction in the United States, and specifically in Delaware, pursuant to Fed. R. Civ. P. 4(k)(2).

10. Venue for these counterclaims is proper in this judicial district pursuant to 28 U.S.C. §§ 1391(b) and (c) and 1400(b).

FACTUAL BACKGROUND

11. Align was founded in 1997 and is a global medical device company with industry leading innovative products such as the iTero intraoral scanner and the Invisalign clear aligner system that help dental and orthodontic professionals deliver effective, cutting-edge dental and restorative and orthodontic options to their patients.

12. Align's iTero intraoral scanners scan and provide, in conjunction with Align's Invisalign orthodontic system, color 3D imaging of an intraoral surface, such as the teeth and gums, without drying and powdering the intraoral surface, resulting in a digital impression. Align's intraoral scanners and the software within the iTero and Invisalign systems that works in conjunction with the scanner thus eliminate the need for traditional teeth impressions typically taken with an elastomeric or other material.

13. The digital impression captured by Align's iTero intraoral scanners, when teamed with Align's Invisalign system, can be used in a variety of dental and orthodontic applications such as, for example, tracking a patient's progress during the Invisalign treatment, tracking changes in a patient's dentition over time, mapping the occlusion of a patient's teeth, and correcting inaccurate scan data.

14. Align's iTero intraoral scanner and Invisalign system constitute a proprietary system and method for treating, among other things, malocclusion, misalignment, and/or chipped or missing teeth using a high-precision, high-speed intraoral scanner and related software to create a variety of orthodontic and dental devices including, but not limited to, crowns, bridges, bracket templates, aligners and implants. Each dental device is custom-manufactured for each patient using computer-aided design techniques and sophisticated computer graphic interfaces to communicate with the patient's dental or orthodontic professional in the planning, implementation, and revision of the customized treatment program.

15. Align's iTero intraoral scanner and Invisalign system developed by Align over many years and at great expense and effort, represent a breakthrough in the manufacturing and principle of "mass customization" and a vast improvement over conventional methods for treating, among other things, chipped or missing teeth, misalignment of teeth and malocclusion. Additionally, the iTero intraoral scanner and Invisalign system provide a "chair-side" platform for live viewing of the digital impression as it is being built on the display screen during scanning, for accessing valuable digital diagnosis and treatment tools, and for enhancing accuracy of records, treatment efficiency, and the overall patient experience. The innovations embodied in Align's iTero intraoral scanner and Invisalign system are protected by numerous United States and foreign patents.

16. Align's iTero scanners do not infringe any claims of the '551 or '042 patents.

17. The '551 and '042 patents, including all claims, are invalid.

18. On information and belief, 3Shape designs, develops, manufactures, and markets the Trios 3 and 4 scanners. Moreover, 3Shape is involved in the sale of and/or importation into the United States of intraoral scanners, digital models, and digital data for dental and orthodontic applications including, but not limited to, crowns, bridges, bracket templates, aligners and implants. 3Shape's intraoral scanners for dental and orthodontic applications described above embody and/or use the patented apparatuses, systems, and methods at issue.

19. 3Shape's website, www.3Shape.com , provides a Webshop for sales of its products and updating subscriptions to its software. 3Shape's website also offers training and videos on how to use the Trios 3 and 4 scanners. Additionally, 3Shape has a YouTube channel with training videos at www.youtube.com/3ShapeTrainingVideos showing how to use the Trios 3 and 4 scanners. 3Shape's website provides information for contacts in the United States for its Sales and 3Shape Academy Training.

20. 3Shape's website further provides a Resources page with user manuals on the products and how to use the products to encourage purchase and use of 3Shape products, including for the Trios 3 and 4 scanners.

21. 3Shape has, directly or through agents and/or intermediaries, attended trade shows in the United States, where it has demonstrated, and continues to demonstrate, the use of the Trios 3 and 4 scanners and its software to the public and orthodontists. 3Shape has, directly or through agents and/or intermediaries, demonstrated the products at trade shows because it hopes that someone will buy its products.

22. On information and belief, 3Shape has, directly or through agents and/or intermediaries, used, sold, and offered for sale its Trios 3 and 4 scanners at conferences in the United States, including the American Association of Orthodontics 2019 Annual Meeting.

23. 3Shape's Trios 3 and 4 scanners directly compete with Align's iTero scanners. On information and belief, 3Shape developed, made and sold its intraoral scanners with the intent to directly compete with Align's intraoral scanners and software. Before introducing its products, 3Shape was aware of the structure, design, and operation of Align's patented intraoral scanners, including but not limited to intraoral scanners developed by Cadent Holdings, Inc. ("Cadent") which Align acquired on April 29, 2011. Moreover, 3Shape has previously entered into agreements with Align that provided 3Shape with significant access to Align's patented technologies.

24. On information and belief, 3Shape developed, made, and sold its infringing Trios 3 and 4 scanners despite having knowledge of the Align Patents-In-Suit based, at a minimum on (i) its knowledge of the Align intraoral scanners being covered by numerous patents including the patent at issue through its prior business dealings with Align, including those with Cadent, whereby 3Shape acquired specific and detailed knowledge from Align regarding the structure, function, operation and commercial benefits of the Align products and the patent protection afforded to certain structures, functions and operations of the patented Align technology; (ii) by virtue of 3Shape's patent prosecution activities wherein 3Shape is aware of Align's patent portfolio (including citing several Align patents on multiple occasions); and/or (iii) by virtue of 3Shape's U.S. Food and Drug Section 510(k) premarket notification of intent to market the accused products which identifies 3Shape's accused products as substantially equivalent to Align's patent practicing products (*see*, *e.g.*, Exhibit 4).

OVERVIEW OF THE PATENTS-IN-SUIT

25. On June 13, 2017, the U.S. Patent and Trademark Office duly and lawfully issued U.S. Patent No. 9,675,430 ("the '430 patent"), entitled "Confocal Imaging Apparatus with Curved Focal Surface" naming Tal Verker, Adi Levin, Ofer Saphier, and Maayan Moshe as the inventors. Align is the owner by assignment of all right, title and interest in the '430 patent and has exclusive right to bring suit to enforce the patent. Evidence of such assignment has been recorded with the U.S. Patent and Trademark Office at Reel/Frame 036430/0819. The claims of the '430 patent are valid and enforceable. A true and correct copy of the '430 patent is attached hereto as Exhibit 1.

26. On December 17, 2019, the U.S. Patent and Trademark Office duly and lawfully issued U.S. Patent No. 10,507,088 ("the '088 patent"), entitled "Confocal Imaging Apparatus with Simplified Optical Design" naming Tal Verker, Adi Levin, Ofer Saphier, and Maayan Moshe as the inventors. Align is the owner by assignment of all right, title and interest in the '088 patent and has exclusive right to bring suit to enforce the patent. Evidence of such assignment has been recorded with the U.S. Patent and Trademark Office at Reel/Frame 048640/0092. The claims of the '088 patent are valid and enforceable. A true and correct copy of the '088 patent is attached hereto as Exhibit 2.

27. On December 17, 2019, the U.S. Patent and Trademark Office duly and lawfully issued U.S. Patent No. 10,507,089 ("the '089 patent"), entitled "Confocal Imaging Apparatus with Curved Focal Surface" naming Tal Verker, Adi Levin, Ofer Saphier, and Maayan Moshe as the inventors. Align is the owner by assignment of all right, title and interest in the '089 patent and has exclusive right to bring suit to enforce the patent. Evidence of such assignment has been recorded with the U.S. Patent and Trademark Office at Reel/Frame 049024/0020. The claims of

the ’089 patent are valid and enforceable. A true and correct copy of the ’089 patent is attached hereto as Exhibit 3.

COUNT I
(Declaratory Judgment of Invalidity of the ’551 Patent)

28. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-13 of the Counterclaims as if fully set forth herein.

29. Align is entitled to a declaration that all claims of the ’551 patent are invalid pursuant to at least 35 U.S.C. §§ 101, 102, 103 and/or 112.

COUNT II
(Declaratory Judgment of Non-Infringement of the ’551 Patent)

30. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-15 of the Counterclaims as if fully set forth herein.

31. Align is entitled to a declaration that it does not infringe any claim of the ’551 patent.

COUNT III
(Declaratory Judgment of Invalidity of the ’042 Patent)

32. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-17 of the Counterclaims as if fully set forth herein.

33. Align is entitled to a declaration that all claims of the ’042 patent are invalid pursuant to at least 35 U.S.C. §§ 101, 102, 103 and/or 112.

COUNT IV
(Declaratory Judgment of Non-Infringement of the ’042 Patent)

34. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-19 of the Counterclaims as if fully set forth herein.

35. Align is entitled to a declaration that it does not infringe any claim of the ’042 patent.

COUNT V
(Infringement of U.S. Patent No. 10,507,088)

36. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-35 of the Counterclaims as if fully set forth herein.

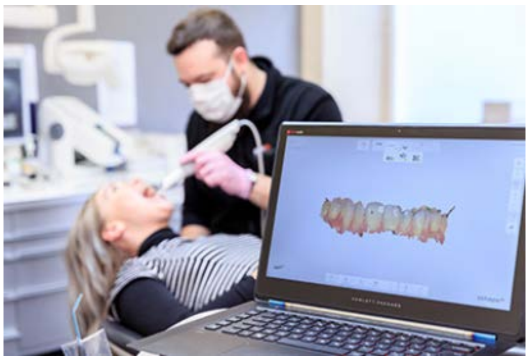
37. On information and belief, 3Shape has been and is now directly and/or indirectly infringing, literally and/or under the doctrine of equivalents, the ’088 patent by making, using, selling, and/or offering for sale in the United States, and/or importing into the United States, products covered by one or more of the claims of the ’088 patent, including the Trios 3 and 4 scanners.

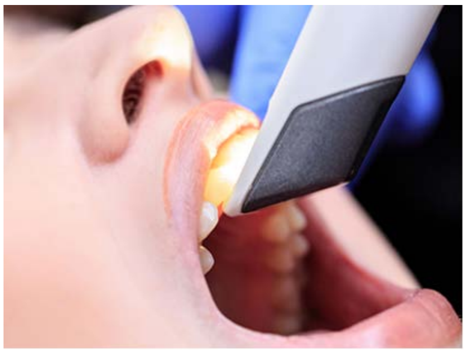
38. The ’088 patent is generally directed to performing intraoral scans. Claim 1 of the ’088 patent recites an imaging apparatus for performing intraoral scans, comprising: a light source to provide light; an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises a non-flat focal surface, and wherein the optical system comprises focusing optics to perform focusing of the light onto the non-flat focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity; a translation mechanism to adjust a location of at least one lens of the plurality of lenses to thereby adjust a focusing setting of the optical system and displace the non-flat focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, and wherein at least one of a shape or a magnification of the non-flat focal surface changes with changes in the focusing setting; and a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the returning light are to be measured for a plurality of

locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface using one or more compensation models that provide different adjustments for different focusing settings of the optical system.

39. Upon information and belief, 3Shape's Trios 3 and 4 scanners infringe at least claim 1 of the '088 patent. For example, 3Shape's Trios 3 and 4 scanners comprise a light source to provide light, as shown in the demonstration video, TRIOS®3 brochure, and press release below.

(*See, e.g.*, Ex. 5, 3Shape TRIOS®3 Digital Impression Scanning (available at: http://www.dts-international.com/trios3).)



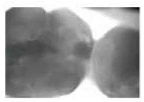


(*Id.*)

Be equipped for success with NEW 3Shape TRIOS innovation

3Shape TRIOS® 4

The most powerful 3Shape intraoral scanner to date!



Caries diagnostic aid*
The world's first intraoral scanner with digital detection of possible surface and interproximal caries** without the need for an additional scanning device.

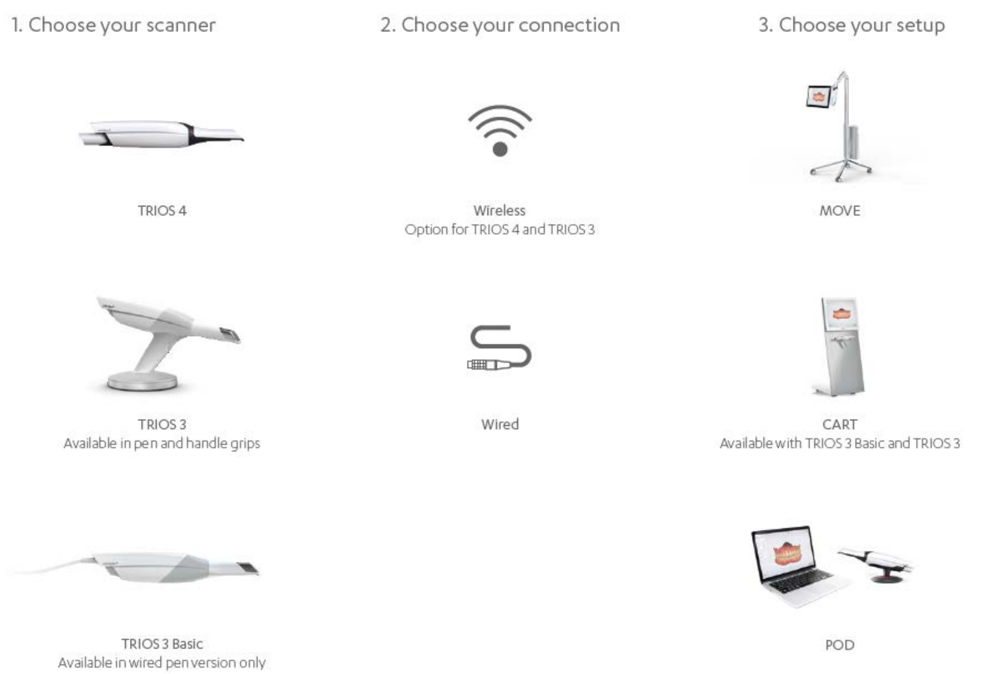
Smart tips
New generation of tips with instant-heat technology so you are scan-ready in seconds, and enabling 30% additional battery life. Plus a dedicated tip to aid the detection of interproximal caries.**

3Shape TRIOS 3 Basic

The entry-level intraoral scanning solution

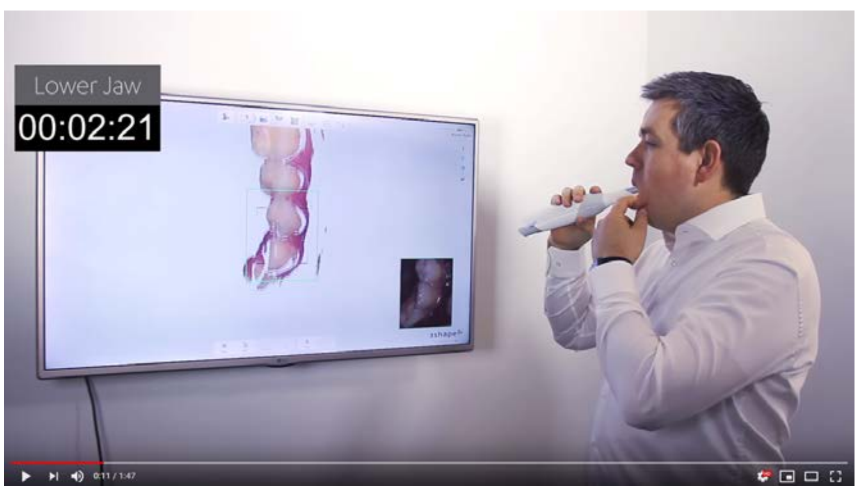
> Core award-winning TRIOS scanning technology.
> Simple 'scan and send-to' workflow.

(*See, e.g.*, 3Shape TRIOS®3 Digital Impression Solution Brochure (3Shape website, available at: https://www.3shape.com/en/scanners/trios-3 (https://embed.widencdn.net/pdf/plus/3shape/9gjkyqthjr/3Shape-TRIOS-2019-Brochure-EN.pdf?u=6xmdhr).)

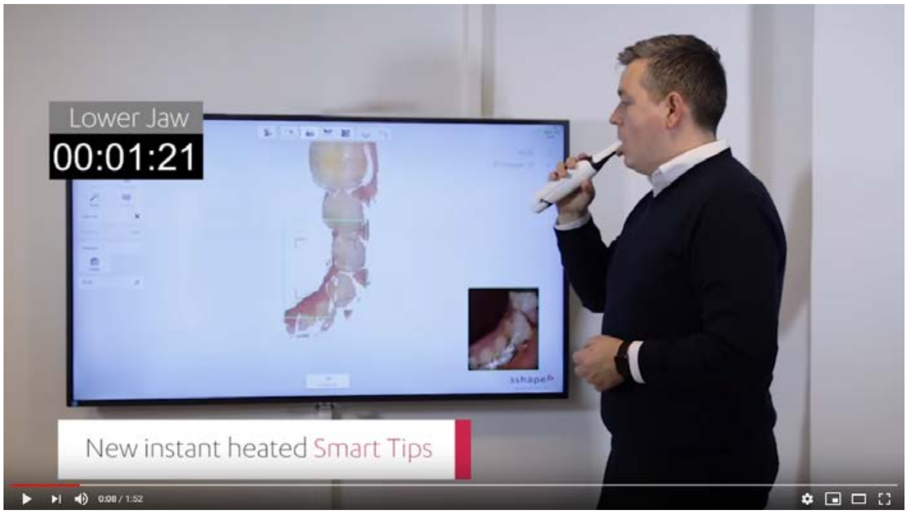


		TRIOS 4	TRIOS 3	TRIOS 3 Basic
Scanner generation		4th	3rd	3rd
Scanner features	Wireless	✓	✓	N/A
	AI scan	✓	✓	✓
	3Shape accuracy	✓	✓	✓
	Real colors and shade measurement	✓	✓	✓
	Smart tips	✓	N/A	N/A
	Caries diagnostic aid*	✓	N/A	N/A

(*Id.*)



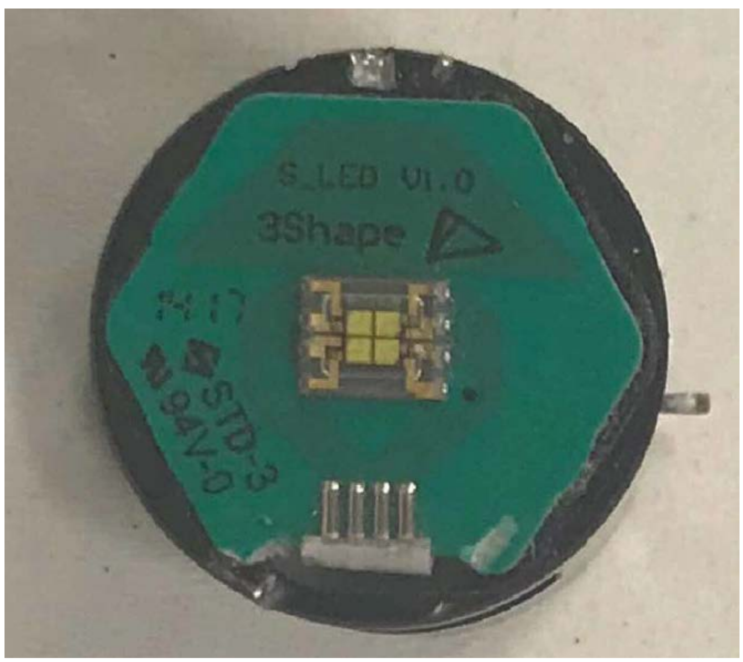
(*See*, *e.g.*, Ex. 7, 3Shape TRIOS®3 Video (*See* 3Shape Trios 3 Wireless Insane Speed in Action, available at: https://www.youtube.com/watch?v=C5jKnxEyrbU).)



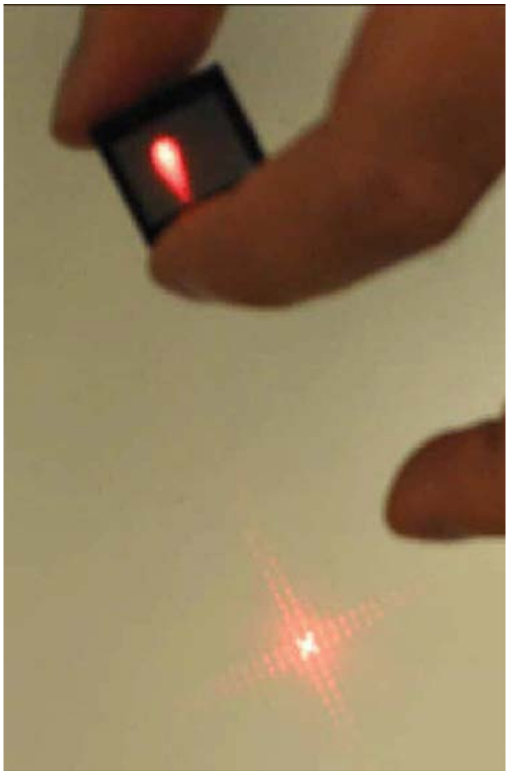
(*See, e.g.*, Ex. 8, 3Shape TRIOS®4 Video (3Shape's Morten Ryde Demonstrates the New 3Shape Trios 4, available at: https://www.youtube.com/watch?v=IJQNd8Ywc3U).)

For example, the Accused Devices practice these feature as shown in the screenshots below:

(Showing an example of light being provided from a light source.)



(Showing an example of a light source for providing light.)



(Showing an example of a light source providing light.)

40. For example, 3Shape's Trios 3 and 4 scanners include an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises a non-flat focal surface, and wherein the optical system comprises focusing optics to perform focusing of the light onto the non-flat focal surface and to direct the light

toward a three dimensional object to be imaged in an oral cavity, as shown, for example, in the demonstration video, TRIOS®3 brochure, and press release below.

(Showing an example of an optical system comprising a plurality of lenses disposed along an optical path of light.)

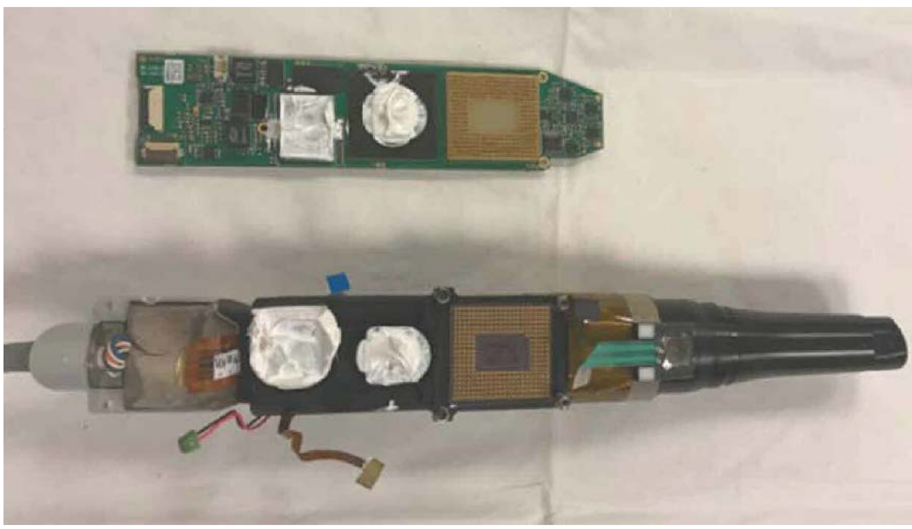
(Showing an example of the focusing optics to perform focusing of the light onto the non-flat focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity.)

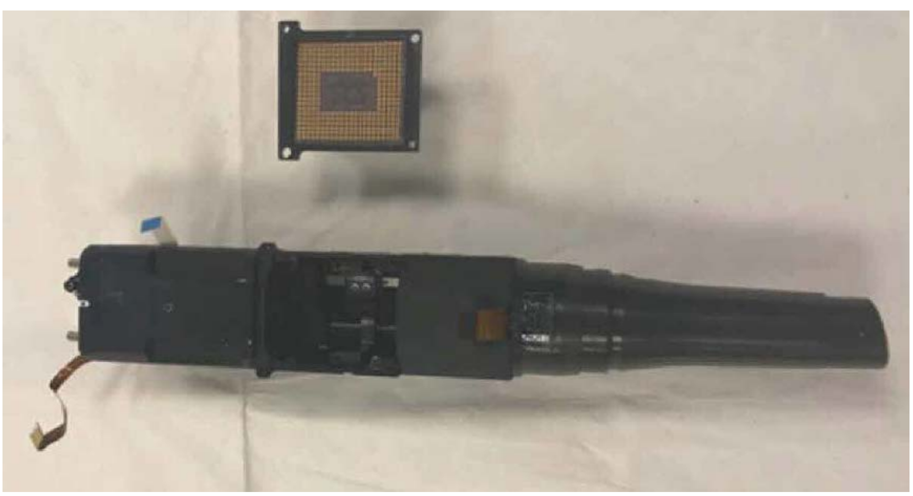
41. For example, 3Shape's Trios 3 and 4 scanners comprise a translation mechanism to adjust a location of at least one lens of the plurality of lenses to thereby adjust a focusing setting of the optical system and displace the non-flat focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, and

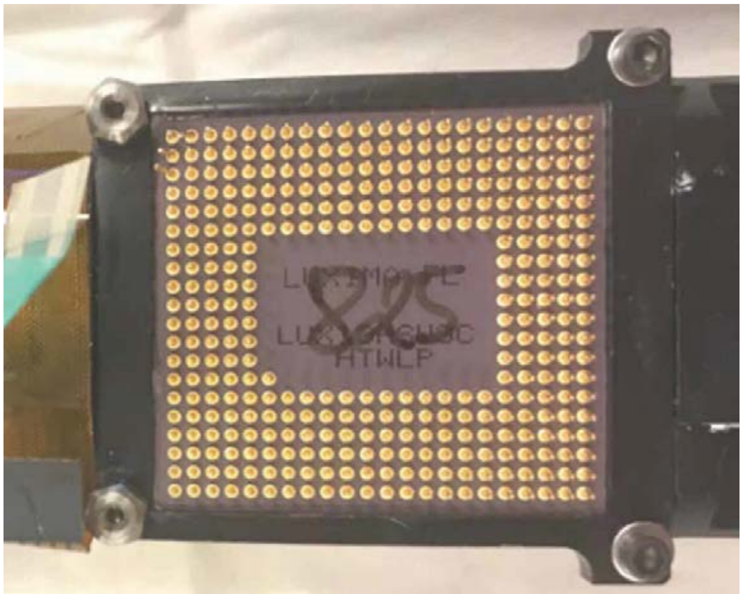
wherein at least one of a shape or a magnification of the non-flat focal surface changes with changes in the focusing setting, as shown, for example, in the pictures below:

(Showing an example of a translation mechanism to adjust a location of at least one lens of the plurality of lenses within the body of the Trios 3 to thereby adjust a focusing setting of the optical system and to displace the non-flat focal surface along an imaging axis defined by the optical path.)

42. On information and belief, 3Shape's Trios 3 and 4 scanners comprise a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the returning light are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface using one or more compensation models that provide different adjustments for different focusing settings of the optical system, as shown, for example, in the pictures below:







(Showing a Luxima image sensor, which is an example of a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics.) On information and belief, the detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface using one or more compensation models that provide different adjustments for different focusing settings of the optical system.

43. 3Shape possesses knowledge of and is aware of the ’088 patent by virtue of, at a minimum, the filing of these Counterclaims and, on information and belief, possessed prior knowledge of the ’088 patent by virtue of the prior business dealings between 3Shape and Align and other facts described above.

44. 3Shape also has been and is now actively inducing infringement of one or more claims of the ’088 patent, either literally or under the doctrine of equivalents.

45. On information and belief, 3Shape alone and/or acting in concert with, directing and/or authorizing 3Shape TRIOS A/S, 3Shape US, and/or 3Shape Manufacturing US, LLC to

make, use, sell or offer for sale in the United States or import into the United States the Trios 3 and 4 scanners possesses an affirmative intent to actively induce infringement by others.

46. On information and belief, 3Shape induces 3Shape TRIOS A/S, 3Shape US, and 3Shape Manufacturing US, LLC to infringe the ’088 patent.

47. 3Shape has intended, and continues to intend to induce infringement of the ’088 patent by others and has knowledge, with specific intent, that the inducing acts would cause infringement or has been willfully blind to the possibility that its inducing acts would cause the infringing acts. For example, 3Shape is aware that the features claimed in the ’088 patent are features in the Trios 3 and 4 scanners and are features used by others that purchase Trios 3 and 4 scanners and, therefore, that purchasers and end users will infringe the ’088 patent by using the Trios 3 and 4 scanners. 3Shape actively induces infringement of the ’088 patent with knowledge and the specific intent to encourage that infringement by, *inter alia,* disseminating the Trios 3 and 4 scanners and providing promotional materials, marketing materials, training materials, instructions, product manuals, user guides, and technical information (including but not limited to the demonstration video, brochure, and press release described in these Counterclaims) to others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners. Those third parties directly infringe the ’088 patent by making, using, selling, offering for sale, and/or importing the Trios 3 and 4 scanners.

48. 3Shape also has been and is now contributing to the infringement of one or more claims of the ’088 patent, either literally or under the doctrine of equivalents.

49. 3Shape has actively, knowingly, and intentionally contributed and continues to actively, knowingly, and intentionally contribute to the infringement of the ’088 patent by having

sold or offered to sell and continuing to sell or offer for sale the Trios 3 and 4 scanners within in the United States and/or by importing the Trios 3 and 4 scanners into the United States, with knowledge that the infringing technology in the Trios 3 and 4 scanners is especially made and/or especially adapted for use in infringement of the ’088 patent. 3Shape has contributed to the infringement by others with knowledge that the infringing technology in the Trios 3 and 4 scanners is a material part of the patented invention, and with knowledge that the infringing technology in the Trios 3 and 4 scanners is not a staple article of commerce suitable for substantial non-infringing use, and with knowledge that others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners infringe and will continue to infringe the ’088 patent because, due to their specific designs, the accused products and components thereof do not have any substantial noninfringing uses. 3Shape has such knowledge at least because the claimed features of the ’088 patent are used by others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners.

50. On information and belief, 3Shape knew or should have known of the ’088 patent and has acted, and continues to act, in an egregious and wanton manner by infringing ’088 patent. On information and belief, 3Shape’s infringement of the ’088 patent has been and continues to be willful and deliberate. The market for intraoral scanners is small and contains a limited number of competitors, with Align being a known pioneer with whom 3Shape has great familiarity. The companies have worked together in the past and 3Shape has had ample access to Align’s technology. Upon information and belief, 3Shape knowingly developed and sold its

competitive knockoff products in an infringing manner that was known to 3Shape or was so obvious that 3Shape should have known about this infringement.

51. On information and belief, despite knowing that its actions constituted infringement of the ’088 patent and/or despite knowing that that there was a high likelihood that its actions constituted infringement of the patent, 3Shape nevertheless continued its infringing actions, and continues to make, use, and sell its infringing products.

52. 3Shape’s acts of infringement have injured and damaged Align. 3Shape’s wrongful conduct has caused Align to suffer irreparable harm resulting from the loss of its lawful patent rights to exclude others from making, using, selling, offering to sell and importing the patented inventions. Upon information and belief, 3Shape will continue these infringing acts unless enjoined by this Court.

COUNT VI
(Infringement of U.S. Patent No. 10,507,089)

53. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-52 of the Counterclaims as if fully set forth herein.

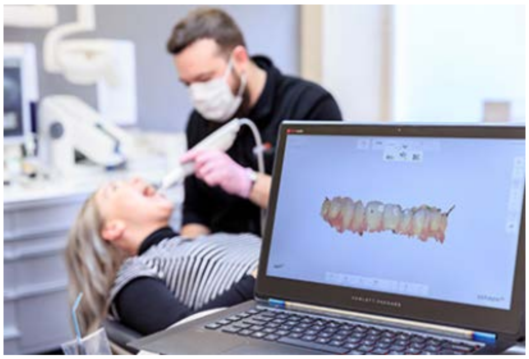
54. On information and belief, 3Shape has been and is now directly and/or indirectly infringing, literally and/or under the doctrine of equivalents, the ’089 patent by making, using, selling, and/or offering for sale in the United States, and/or importing into the United States, products covered by one or more of the claims of the ’089 patent, including the Trios 3 and 4 scanners.

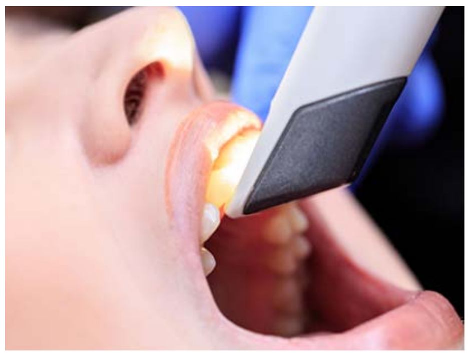
55. The ’089 patent is generally directed to an imaging apparatus for performing intraoral scans. Claim 9 of the ’089 patent recites an imaging apparatus for performing intraoral scans, comprising: a light source to provide light; an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing

optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity; a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, wherein at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens; a detector to generate surface scan data by measuring returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the returning light is to be measured for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object, the surface scan data comprising the depth data; and one or more processor to: adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models, wherein the one or more compensation models compensate for changes in magnification associated with different locations of the at least one lens, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens; and generate a three-dimensional virtual model using the adjusted depth data.

56. Upon information and belief, 3Shape's Trios 3 and 4 scanners infringe at least claim 9 of the '089 patent. For example, 3Shape's Trios 3 and 4 scanners comprise a light source to provide light, as shown, for example, in the demonstration video, TRIOS®3 brochure, and press release below:

(*See*, *e.g.*, Ex. 5, 3Shape TRIOS®3 Digital Impression Scanning (available at: http://www.dts-international.com/trios3).)

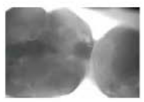




(*Id*.)

Be equipped for success with
NEW 3Shape TRIOS innovation

3Shape TRIOS® 4
The most powerful 3Shape intraoral scanner to date!



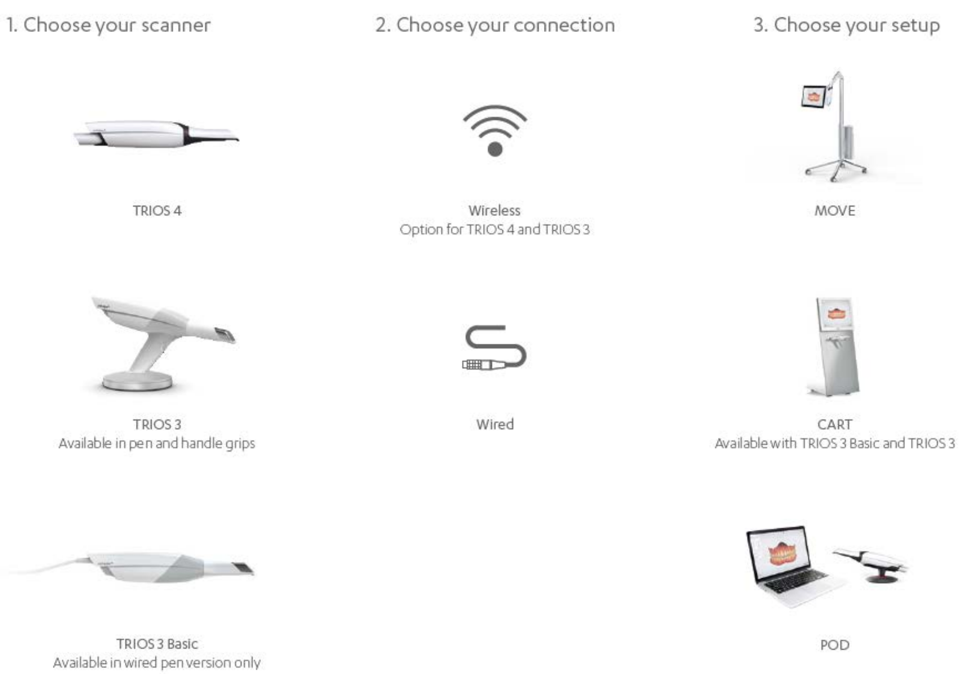
Caries diagnostic aid*
The world's first intraoral scanner with digital detection of possible surface and interproximal caries** without the need for an additional scanning device.

Smart tips
New generation of tips with instant-heat technology so you are scan-ready in seconds, and enabling 30% additional battery life. Plus a dedicated tip to aid the detection of interproximal caries.**

3Shape TRIOS 3 Basic
The entry-level intraoral scanning solution

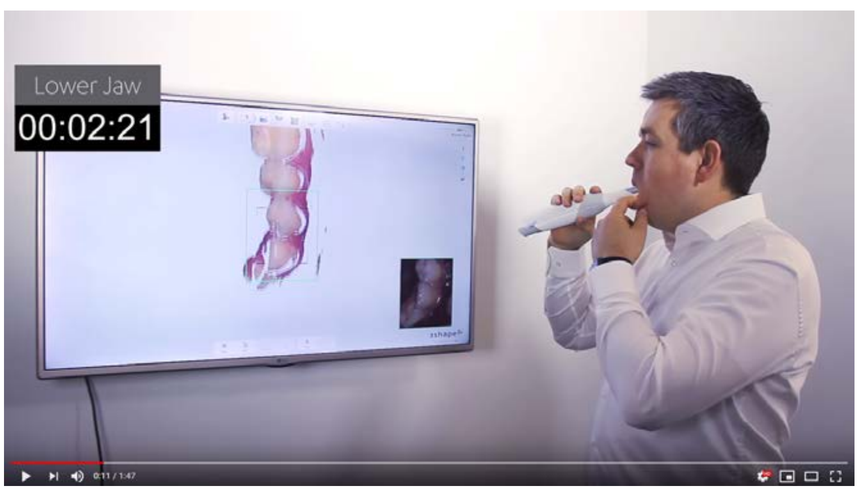
> Core award-winning TRIOS scanning technology.
> Simple 'scan and send-to' workflow.

(*See, e.g.*, 3Shape TRIOS®3 Digital Impression Solution Brochure (3Shape website, available at: https://www.3shape.com/en/scanners/trios-3 (https://embed.widencdn.net/pdf/plus/3shape/9gjkyqthjr/3Shape-TRIOS-2019-Brochure-EN.pdf?u=6xmdhr).)

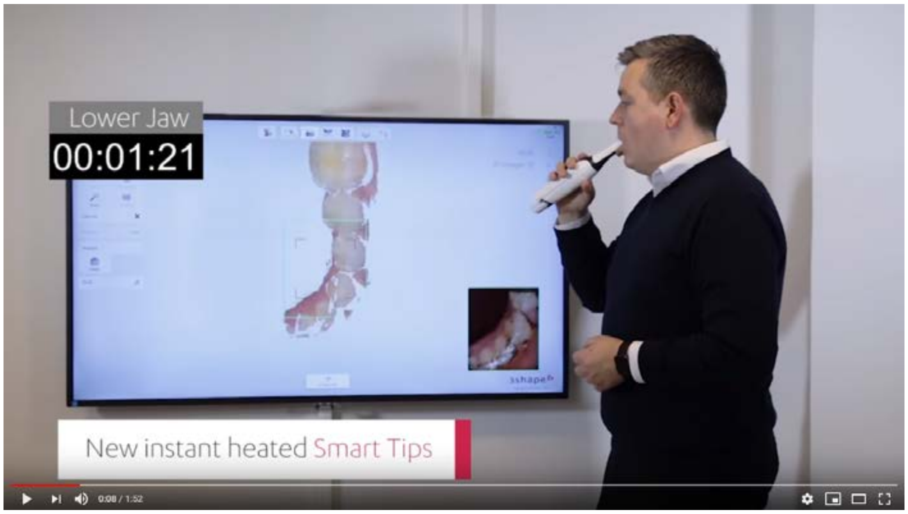


		TRIOS 4	TRIOS 3	TRIOS 3 Basic
Scanner generation		4th	3rd	3rd
Scanner features	Wireless	✓	✓	N/A
	AI scan	✓	✓	✓
	3Shape accuracy	✓	✓	✓
	Real colors and shade measurement	✓	✓	✓
	Smart tips	✓	N/A	N/A
	Caries diagnostic aid*	✓	N/A	N/A

(*Id*.)

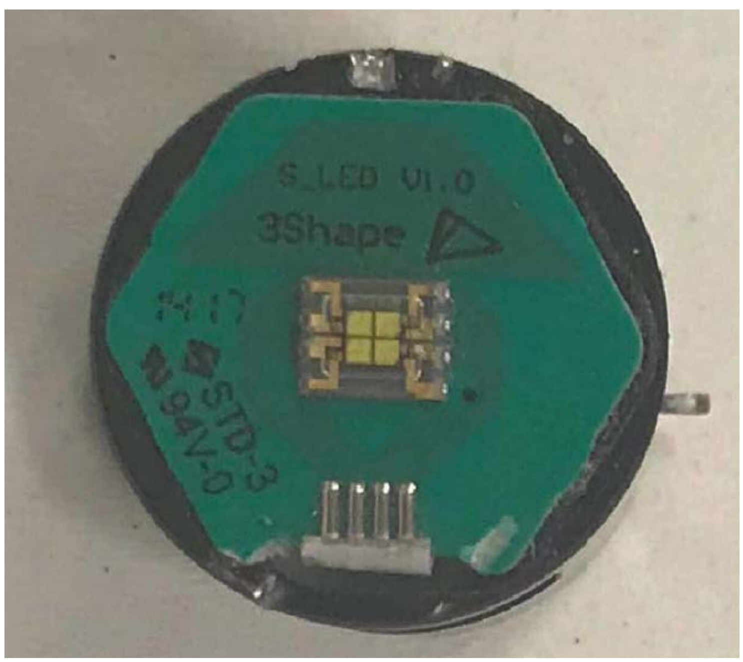


(*See*, *e.g*., Ex. 7, 3Shape TRIOS®3 Video (*See* 3Shape Trios 3 Wireless Insane Speed in Action, available at: https://www.youtube.com/watch?v=C5jKnxEyrbU).)

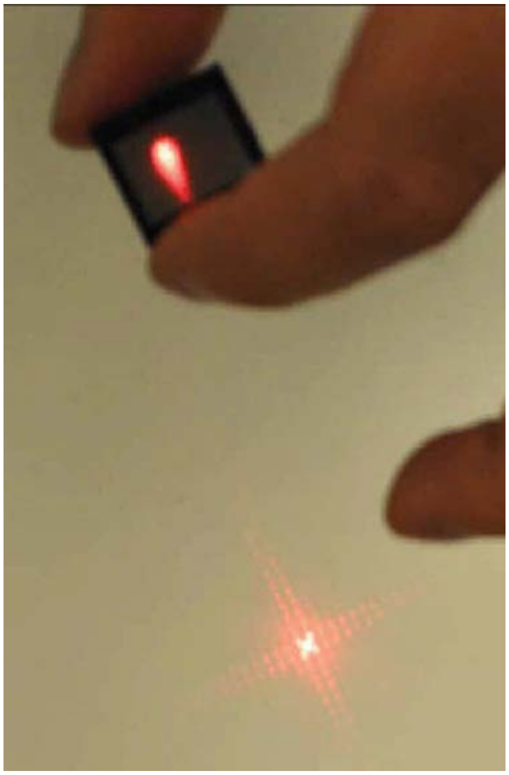


(*See, e.g.*, Ex. 8, 3Shape TRIOS®4 Video (3Shape's Morten Ryde Demonstrates the New 3Shape Trios 4, available at: https://www.youtube.com/watch?v=IJQNd8Ywc3U).)

(Showing an example of a light source for providing light.)



(Showing an example of a light source for providing light.)



(Showing an example of light provided by a light source in the Trios.)

57. For example, 3Shape's Trios 3 and 4 scanners comprise an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing optics to perform focusing of the light onto a focal surface and to

direct the light toward a three dimensional object to be imaged in an oral cavity, as shown, for example, in the pictures below:

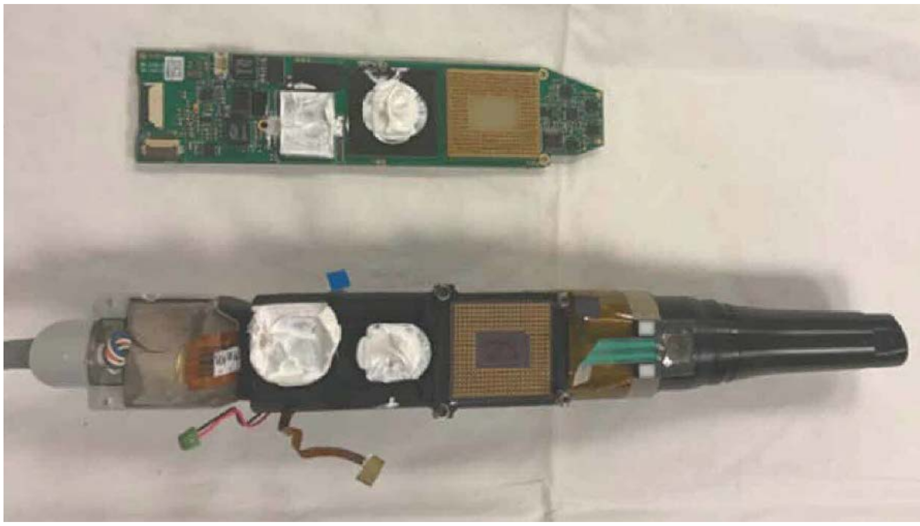
(Showing an example of an optical system comprising a plurality of lenses disposed along an optical path, including focusing optics.)

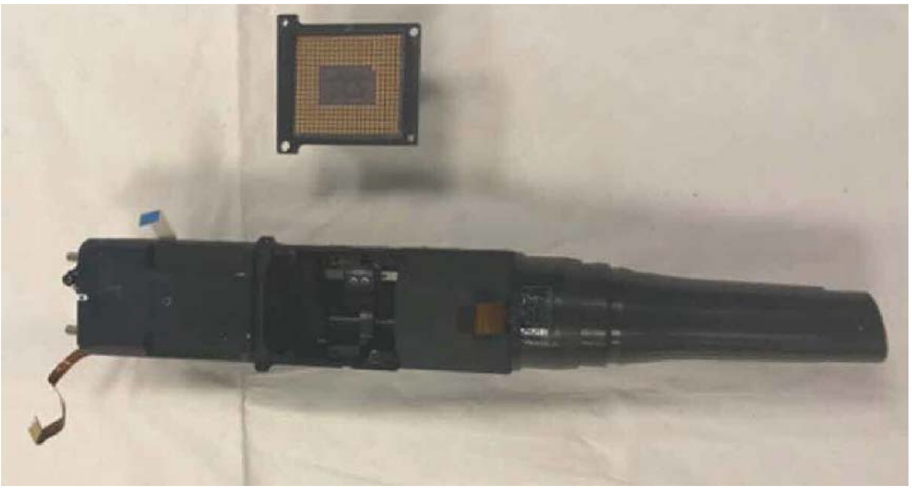
(Showing an example of the focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity.)

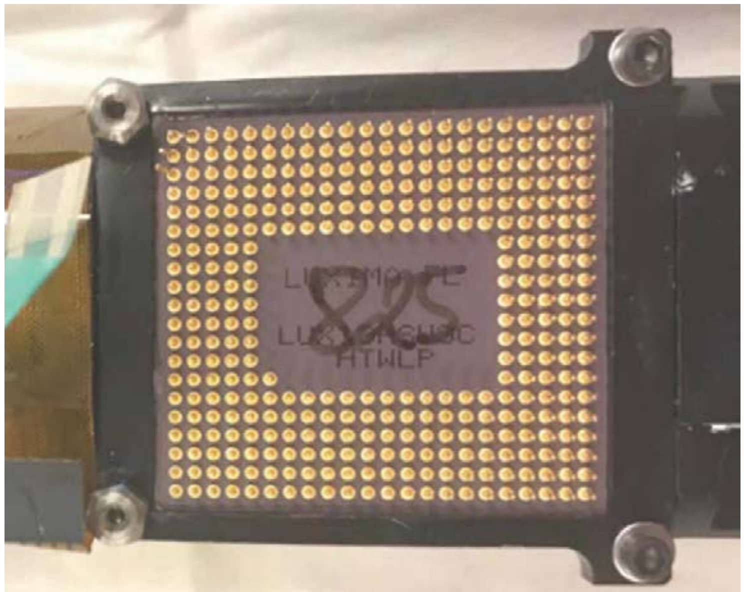
58. For example, 3Shape's Trios 3 and 4 scanners comprise a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, wherein at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens, as shown, for example, in the pictures below:

(Showing an example of a translation mechanism to adjust a location of at least one lens of the plurality of lenses within the body of the Trios 3 to displace the focal surface along an imaging axis defined by the optical path.) On information and belief, at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens.

59. For example, 3Shape's Trios 3 and 4 scanners comprise a detector to generate surface scan data by measuring returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the returning light is to be measured for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object, the surface scan data comprising the depth data, as shown, for example, in the pictures below:

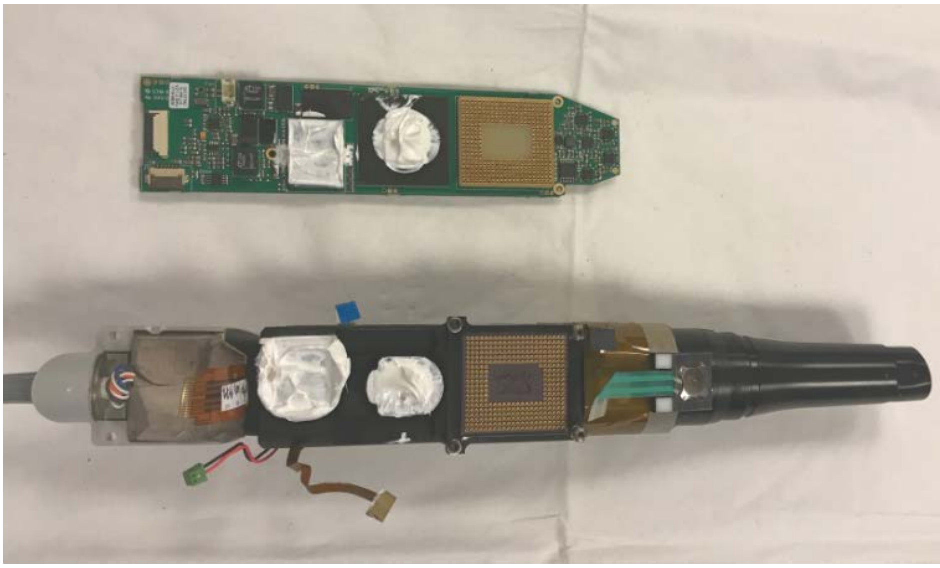


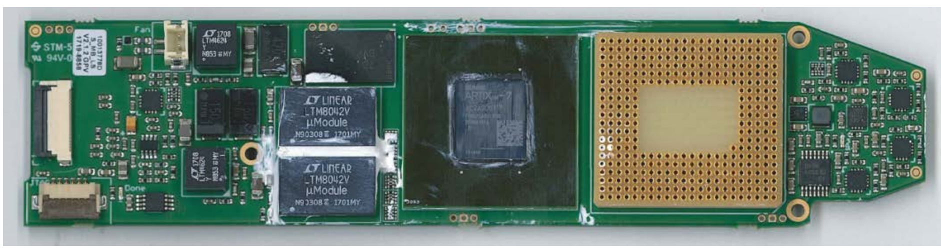


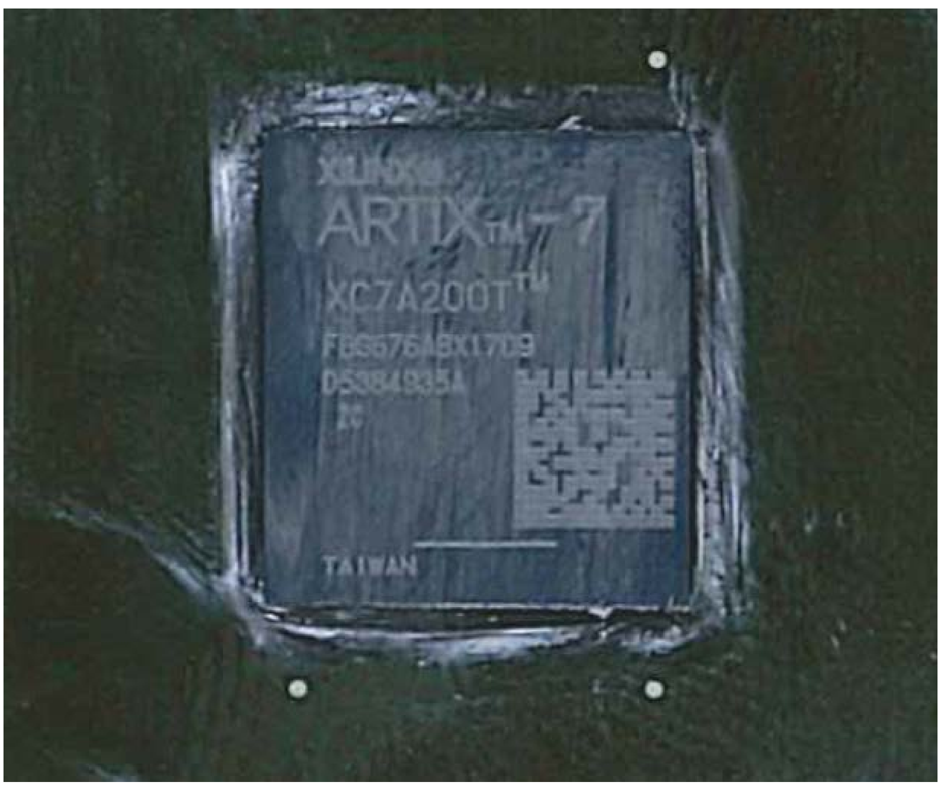


(Showing a Luxima image sensor, which is an example of a detector for measuring returning light that is reflected off of the three dimensional object.) On information and belief, the detector generates surface scan data by measuring returning light for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object. On information and belief, the surface scan data comprises depth data.

60. For example, 3Shape's Trios 3 and 4 scanners comprise one or more processor to: adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models, wherein the one or more compensation models compensate for changes in magnification associated with different locations of the at least one lens, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens; and generate a three-dimensional virtual model using the adjusted depth data.




LINEAR
LTM8042V
µModule
LINEAR
LTM8042V
µModule


XILINX
ARTIX-7
XC7A200T
FBG676ABX1709
D5384935A
TAIWAN

(Showing an Artix-7, which includes a FPGA processor used to adjust adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models.)

Artix-7 Product Advantage

Artix®-7 devices provide the highest performance-per-watt fabric, transceiver line rates, DSP processing, and AMS integration in a cost-optimized FPGA. Featuring the MicroBlaze™ soft processor and 1,066Mb/s DDR3 support, the family is the best value for a variety of cost and power-sensitive applications including software-defined radio, machine vision cameras, and low-end wireless backhaul.

(*See*, *e.g.*, https://www.xilinx.com/products/silicon-devices/fpga/artix-7.html.)

MicroBlaze Soft Processor Core

MicroBlaze™ is a key element of Xilinx's Embedded Product Portfolio. As a full-featured, FPGA optimized 32-bit Reduced Instruction Set Computer (RISC) soft processor, Microblaze meet requirements for diverse applications such as industrial, medical, automotive, consumer, and communication infrastructure markets among others. MicroBlaze is a highly configurable and easy to use processor and can be used across FPGAs and All Programmable (AP) SoC families. It is included free with Vivado® Design and System Edition and Vivado Webpack Edition. It is also available as part of legacy IDS embedded edition for older FPGA device families like Spartan®-6, Virtex®-6 etc.

MicroBlaze is highly configurable IP core supporting 70+ configuration options. Some of the key configuration options are Instruction/Data Cache, Floating Point unit, Memory Management Unit etc. With highly flexible and configurable core, user can implement virtually any processor use case, from a very-small-footprint state machine or microcontroller to a high-performance, compute-intensive microprocessor-based system running Linux. The IP can be configured to operate in either a three-stage pipeline mode (to optimize for size), or in a five-stage pipeline mode (to optimize for speed)—thus delivering faster DMIPs performance than any other FPGA-based soft processing solution.

(*See*, *e.g.*, https://www.xilinx.com/products/design-tools/microblaze.html.) On information and belief, the one or more compensation moels compensate for changes in magnification associated with different locations of the at least one lens. On information and belief, the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens. On information and belief, the processor generates a three-dimsnional virtual model using the adjusted depth data.

61. 3Shape possesses knowledge of and is aware of the ’089 patent by virtue of, at a minimum, the filing of these Counterclaims and, on information and belief, possessed prior knowledge of the ’089 patent by virtue of the prior business dealings between 3Shape and Align and other facts described above.

62. 3Shape also has been and is now actively inducing infringement of one or more claims of the ’089 patent, either literally or under the doctrine of equivalents.

63. On information and belief, 3Shape alone and/or acting in concert with, directing and/or authorizing 3Shape TRIOS A/S, 3Shape US and/or 3Shape Manufacturing US, LLC to make, use, sell or offer for sale in the United States or import into the United States the Trios 3 and 4 scanners possesses an affirmative intent to actively induce infringement by others.

64. On information and belief, 3Shape induces 3Shape TRIOS A/S, 3Shape US, and 3Shape Manufacturing US, LLC to infringe the ’089 patent.

65. 3Shape has intended, and continues to intend to induce infringement of the ’089 patent by others and has knowledge, with specific intent, that the inducing acts would cause infringement or has been willfully blind to the possibility that its inducing acts would cause the infringing acts. For example, 3Shape is aware that the features claimed in the ’089 patent are features in the Trios 3 and 4 scanners and are features used by others that purchase Trios 3 and 4 scanners and, therefore, that purchasers and end users will infringe the ’089 patent by using the Trios 3 and 4 scanners. 3Shape actively induces infringement of the ’089 patent with knowledge and the specific intent to encourage that infringement by, *inter alia*, disseminating the Trios 3 and 4 scanners and providing promotional materials, marketing materials, training materials, instructions, product manuals, user guides, and technical information (including but not limited to the demonstration video, brochure, and press release described in these Counterclaims) to others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners. Those third parties directly infringe the ’089 patent by making, using, selling, offering for sale, and/or importing the Trios 3 and 4 scanners.

66. 3Shape also has been and is now contributing to the infringement of one or more claims of the ’089 patent, either literally or under the doctrine of equivalents.

67. 3Shape has actively, knowingly, and intentionally contributed and continues to actively, knowingly, and intentionally contribute to the infringement of the ’089 patent by having sold or offered to sell and continuing to sell or offer for sale the Trios 3 and 4 scanners within in the United States and/or by importing the Trios 3 and 4 scanners into the United States, with knowledge that the infringing technology in the Trios 3 and 4 scanners is especially made and/or especially adapted for use in infringement of the ’089 patent. 3Shape has contributed to the infringement by others with knowledge that the infringing technology in the Trios 3 and 4 scanners is a material part of the patented invention, and with knowledge that the infringing technology in the Trios 3 and 4 scanners is not a staple article of commerce suitable for substantial non-infringing use, and with knowledge that others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners infringe and will continue to infringe the ’430 patent because, due to their specific designs, the accused products and components thereof do not have any substantial noninfringing uses. 3Shape has such knowledge at least because the claimed features of the ’089 patent are used by others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners.

68. On information and belief, 3Shape knew or should have known of the ’089 patent and has acted, and continues to act, in an egregious and wanton manner by infringing ’089 patent. On information and belief, 3Shape’s infringement of the ’089 patent has been and continues to be willful and deliberate. The market for intraoral scanners is small and contains a

limited number of competitors, with Align being a known pioneer with whom 3Shape has great familiarity. The companies have worked together in the past and 3Shape has had ample access to Align's technology. Upon information and belief, 3Shape knowingly developed and sold its competitive knockoff products in an infringing manner that was known to 3Shape or was so obvious that 3Shape should have known about this infringement.

69. On information and belief, despite knowing that its actions constituted infringement of the '089 patent and/or despite knowing that that there was a high likelihood that its actions constituted infringement of the patent, 3Shape nevertheless continued its infringing actions, and continues to make, use, and sell its infringing products.

70. 3Shape's acts of infringement have injured and damaged Align. 3Shape's wrongful conduct has caused Align to suffer irreparable harm resulting from the loss of its lawful patent rights to exclude others from making, using, selling, offering to sell and importing the patented inventions. Upon information and belief, 3Shape will continue these infringing acts unless enjoined by this Court.

COUNT VII
(Infringement of U.S. Patent No. 9,675,430)

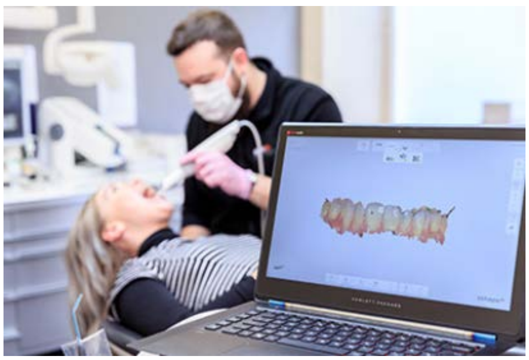
71. Counterclaim-Plaintiff restates and realleges each of the foregoing paragraphs 1-70 of the Counterclaims as if fully set forth herein.

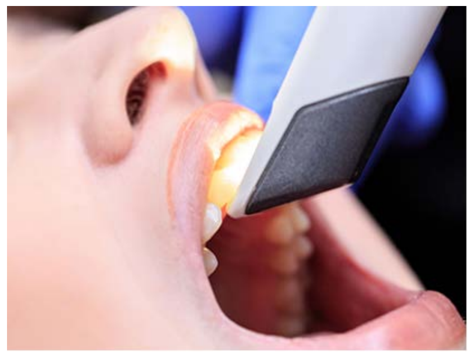
72. On information and belief, 3Shape has been and is now directly and/or indirectly infringing, literally and/or under the doctrine of equivalents, the '430 patent by making, using, selling, and/or offering for sale in the United States, and/or importing into the United States, products covered by one or more of the claims of the '430 patent, including the Trios 3 and 4 scanners.

73. The '430 patent is generally directed to determining and imaging three-dimensional structures. Claim 1 of the '430 patent recites a confocal imaging apparatus comprising: an illumination module to generate an array of light beams; focusing optics comprising a plurality of lenses disposed along an optical path of the array of light beams, the focusing optics to perform confocal focusing of the array of light beams onto a non-flat focal surface and to direct the array of light beams toward a three dimensional object to be imaged; a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the non-flat focal surface along an imaging axis defined by the optical path; and a detector to measure intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the array of returning light beams are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface.

74. Upon information and belief, 3Shape's Trios 3 and 4 scanners infringe at least claim 1 of the '430 patent. For example, 3Shape's Trios 3 and 4 scanners comprise an illumination module to generate an array of light beams, as shown, for example, in the demonstration video, TRIOS®3 brochure, and press release below.

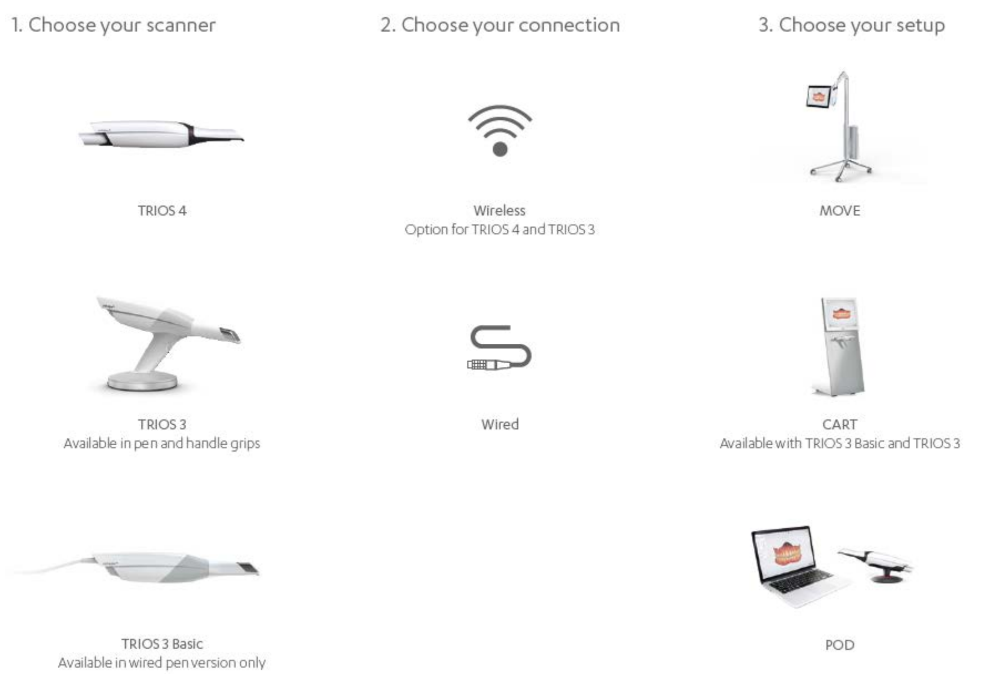
(*See*, *e.g.*, Ex. 5, 3Shape TRIOS®3 Digital Impression Scanning (available at: http://www.dts-international.com/trios3).)





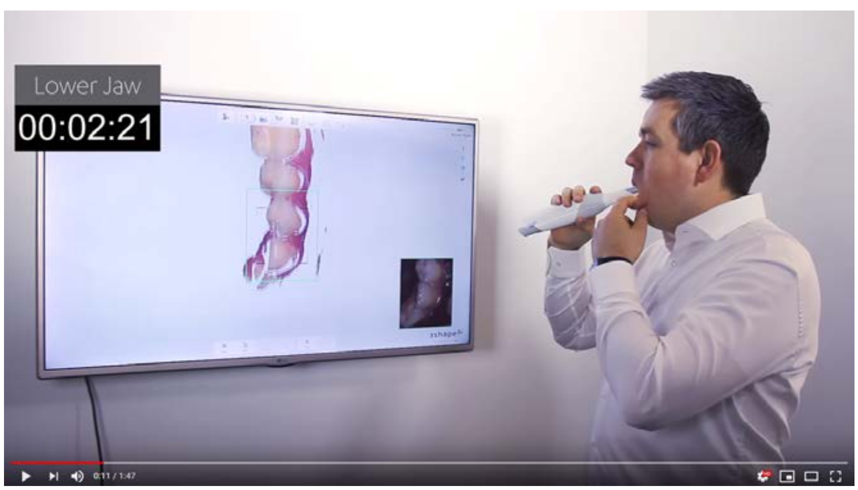
(*Id*.)

(*See, e.g.*, 3Shape TRIOS®3 Digital Impression Solution Brochure (3Shape website, available at: https://www.3shape.com/en/scanners/trios-3 (https://embed.widencdn.net/pdf/plus/3shape/9gjkyqthjr/3Shape-TRIOS-2019-Brochure-EN.pdf?u=6xmdhr).)

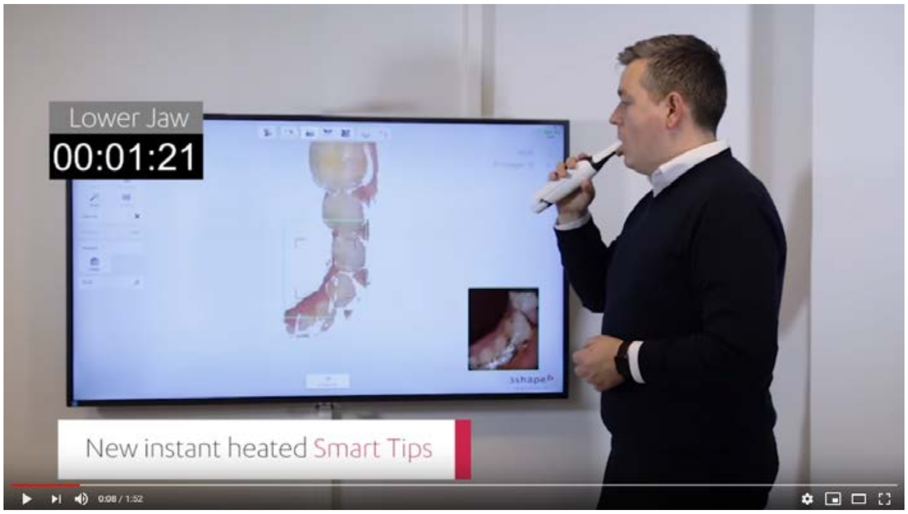


		TRIOS 4	TRIOS 3	TRIOS 3 Basic
Scanner generation		4th	3rd	3rd
Scanner features	Wireless	✓	✓	N/A
	AI scan	✓	✓	✓
	3Shape accuracy	✓	✓	✓
	Real colors and shade measurement	✓	✓	✓
	Smart tips	✓	N/A	N/A
	Caries diagnostic aid*	✓	N/A	N/A

(*Id.*)



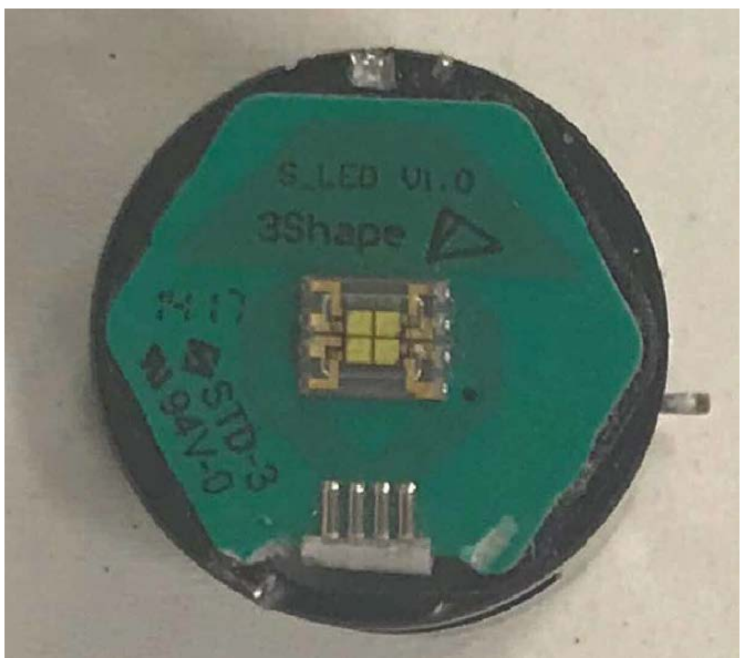
(*See*, *e.g.*, Ex. 7, 3Shape TRIOS®3 Video (*See* 3Shape Trios 3 Wireless Insane Speed in Action, available at: https://www.youtube.com/watch?v=C5jKnxEyrbU).)



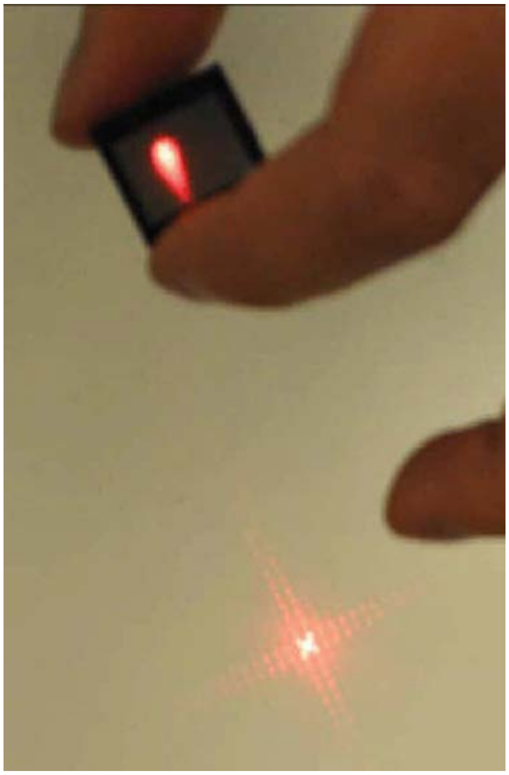
(*See*, *e.g.*, Ex. 8, 3Shape TRIOS®4 Video (3Shape's Morten Ryde Demonstrates the New 3Shape Trios 4, available at: https://www.youtube.com/watch?v=IJQNd8Ywc3U).)

For example, the Accused Devices practice these feature as shown in the screenshots below:

(Showing an example of an array of light beams being generated.)



(Showing an example of an illumination module configured to generate an array of light beams.)



(Showing an example of an array of light beams.)

75. For example, 3Shape's Trios 3 and 4 scanners comprise focusing optics comprising a plurality of lenses disposed along an optical path of the array of light beams, the focusing optics to perform confocal focusing of the array of light beams onto a non-flat focal surface and to direct the array of light beams toward a three dimensional object to be imaged, as

shown, for example, in the screenshots, demonstration video, TRIOS®3 brochure, and press release below.

(Showing an example of the focusing optics to perform confocal focusing of the array of light beams onto a non-flat focal surface and to direct the array of light beams toward a three dimensional object to be imaged.)

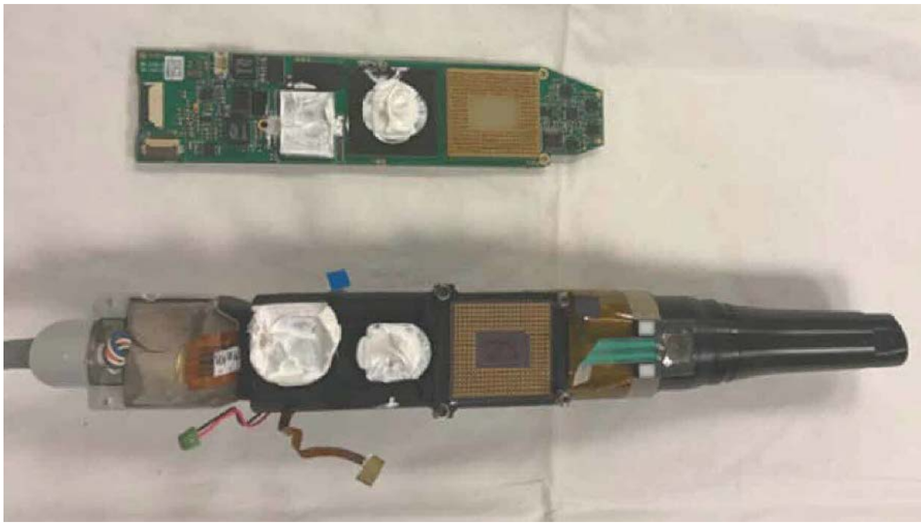
(Showing an example of focusing optics comprising a plurality of lenses disposed along an optical path of the array of light beams.)

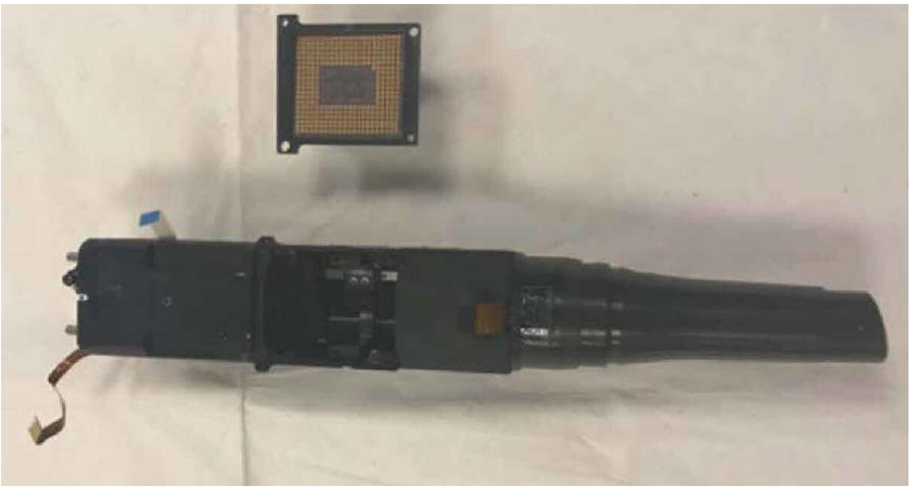
76. For example, 3Shape's Trios 3 and 4 scanners comprise a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the non-flat focal surface along an imaging axis defined by the optical path, as shown, for example, in the pictures below:

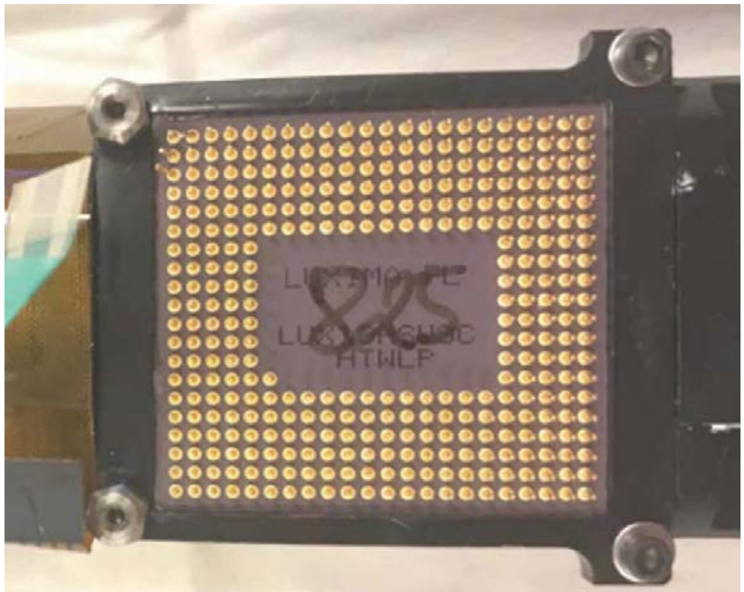
(Showing an example of a translation mechanism to adjust a location of at least one lens of the plurality of lenses within the body of the Trios 3 to displace the focal surface along an imaging axis defined by the optical path.)

77. On information and belief, 3Shape's Trios 3 and 4 scanners comprise a detector to measure intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the

array of returning light beams are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface, as shown, for example, in the pictures below:







(Showing a Luxima image sensor, which is an example of a detector to measure intensities of an array of returning light beams that are reflected from the three-dimensional object and directed back through the focusing optics.) On information and belief, the intensities of the array of returning light beams are measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three-dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface.

78. 3Shape possesses knowledge of and is aware of the ’430 patent by virtue of, at a minimum, the filing of the Complaint in 1:19-cv-02098 and, on information and belief, possessed prior knowledge of the ’430 patent by virtue of the prior business dealings between 3Shape and Align and other facts described above.

79. 3Shape also has been and is now actively inducing infringement of one or more claims of the ’430 patent, either literally or under the doctrine of equivalents.

80. On information and belief, 3Shape alone and/or acting in concert with, directing and/or authorizing 3Shape TRIOS A/S, 3Shape US and/or 3Shape Manufacturing US, LLC to

make, use, sell or offer for sale in the United States or import into the United States the Trios 3 and 4 scanners possesses an affirmative intent to actively induce infringement by others.

81. On information and belief, 3Shape induces 3Shape TRIOS A/S, 3Shape US, and/or 3Shape Manufacturing US, LLC to infringe the ’430 patent.

82. 3Shape has intended, and continues to intend to induce infringement of the ’430 patent by others and has knowledge, with specific intent, that the inducing acts would cause infringement or has been willfully blind to the possibility that its inducing acts would cause the infringing acts. For example, 3Shape is aware that the features claimed in the ’430 patent are features in the Trios 3 and 4 scanners and are features used by others that purchase Trios 3 and 4 scanners and, therefore, that purchasers and end users will infringe the ’430 patent by using the Trios 3 and 4 scanners. 3Shape actively induces infringement of the ’430 patent with knowledge and the specific intent to encourage that infringement by, *inter alia,* disseminating the Trios 3 and 4 scanners and providing promotional materials, marketing materials, training materials, instructions, product manuals, user guides, and technical information (including but not limited to the demonstration video, brochure, and press release described in these Counterclaims) to others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners. Those third parties directly infringe the ’430 patent by making, using, selling, offering for sale, and/or importing the Trios 3 and 4 scanners.

83. 3Shape also has been and is now contributing to the infringement of one or more claims of the ’430 patent, either literally or under the doctrine of equivalents.

84. 3Shape has actively, knowingly, and intentionally contributed and continues to actively, knowingly, and intentionally contribute to the infringement of the ’430 patent by having

sold or offered to sell and continuing to sell or offer for sale the Trios 3 and 4 scanners within in the United States and/or by importing the Trios 3 and 4 scanners into the United States, with knowledge that the infringing technology in the Trios 3 and 4 scanners is especially made and/or especially adapted for use in infringement of the ’430 patent. 3Shape has contributed to the infringement by others with knowledge that the infringing technology in the Trios 3 and 4 scanners is a material part of the patented invention, and with knowledge that the infringing technology in the Trios 3 and 4 scanners is not a staple article of commerce suitable for substantial non-infringing use, and with knowledge that others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners infringe and will continue to infringe the ’430 patent because, due to their specific designs, the accused products and components thereof do not have any substantial noninfringing uses. 3Shape has such knowledge at least because the claimed features of the ’430 patent are used by others including, but not limited to, resellers, distributors, customers, dentists, orthodontists, dental and orthodontic labs, and/or other end users of the Trios 3 and 4 scanners.

85. On information and belief, 3Shape knew or should have known of the ’430 patent and has acted, and continues to act, in an egregious and wanton manner by infringing ’430 patent. On information and belief, 3Shape’s infringement of the ’430 patent has been and continues to be willful and deliberate. The market for intraoral scanners is small and contains a limited number of competitors, with Align being a known pioneer with whom 3Shape has great familiarity. The companies have worked together in the past and 3Shape has had ample access to Align’s technology. Upon information and belief, 3Shape knowingly developed and sold its

competitive knockoff products in an infringing manner that was known to 3Shape or was so obvious that 3Shape should have known about this infringement.

86. On information and belief, despite knowing that its actions constituted infringement of the ’430 patent and/or despite knowing that that there was a high likelihood that its actions constituted infringement of the patent, 3Shape nevertheless continued its infringing actions, and continues to make, use, and sell its infringing products.

87. 3Shape’s acts of infringement have injured and damaged Align. 3Shape’s wrongful conduct has caused Align to suffer irreparable harm resulting from the loss of its lawful patent rights to exclude others from making, using, selling, offering to sell and importing the patented inventions. Upon information and belief, 3Shape will continue these infringing acts unless enjoined by this Court.

PRAYER FOR RELIEF

WHEREFORE, Counterclaim-Plaintiff respectfully requests that this Court enter a judgment in their favor and against Counterclaim-Defendant as follows:

A. Dismissing the Complaint with prejudice and entering judgment for Counterclaim-Plaintiff;

B. Declaring that Align has not infringed any valid and enforceable claim of the ’551 patent;

C. Declaring that all claims of the ’551 patent are invalid;

D. Declaring that Align has not infringed any valid and enforceable claim of the ’042 patent;

E. Declaring that all claims of the ’042 patent are invalid;

F. Awarding Counterclaim-Plaintiff its reasonable attorneys’ fees, costs, and expenses incurred in this action;

G. Entering judgment that 3Shape has infringed each of the ’088, ’089, and ’430 patents-in-suit;

H. Entering judgment that each of the ’088, ’089, and ’430 patents-in-suit is valid and enforceable;

I. Permanently enjoining 3Shape, their parents, subsidiaries, affiliates, agents, servants, employees, attorneys, representatives, successors, and assigns, and all others in active concert or participation with them from infringing the ’088, ’089, and ’430 patents-in-suit;

J. Ordering an award of damages to Align in an amount adequate to compensate Align for 3Shape’s infringement, said damages to be no less than a reasonable royalty;

K. Entering judgment that the infringement was willful and treble damages pursuant to 35 U.S.C. § 284;

L. Ordering an accounting to determine the damages to be awarded to Align as a result of 3Shape’s infringement, including an accounting for infringing sales not presented at trial and award additional damages for any such infringing sales;

M. Assessing pre-judgment and post judgment interest and costs against 3Shape, together with an award of such interest and costs, in accordance with 35 U.S.C. § 284;

N. Rendering a finding that this case is “exceptional” and award to Align its costs, expenses and reasonable attorneys’ fees, as provided by 35 U.S.C. § 285; and

O. Awarding any such other and further relief as this Court may deem proper.

/s/ Jeff Castellano
John W. Shaw (No. 3362)
Karen E. Keller (No. 4489)
Jeff Castellano (No. 4837)
SHAW KELLER LLP
I.M. Pei Building
1105 North Market Street, 12th Floor
Wilmington, DE 19801
(302) 298-0700
jshaw@shawkeller.com
kkeller@shawkeller.com
jcastellano@shawkeller.com
Attorneys for Defendant

OF COUNSEL:
Blair M. Jacobs
Christina A. Ondrick
Elizabeth Bernard
John S. Holley
Mark Consilvio
PAUL HASTINGS LLP
875 15th Street, N.W.
Washington, DC 20005
(202) 551-1700

Thomas A. Counts
PAUL HASTINGS LLP
101 California Street, 48th Floor
San Francisco, CA 94111
(410) 856-7000

Dated: December 20, 2019

Exhibit 1

US009675430B2

(12) **United States Patent**
Verker et al.

(10) **Patent No.: US 9,675,430 B2**
(45) **Date of Patent: Jun. 13, 2017**

(54) **CONFOCAL IMAGING APPARATUS WITH CURVED FOCAL SURFACE**

(71) Applicant: **Align Technology, Inc.**, San Jose, CA (US)

(72) Inventors: **Tal Verker**, Ofra (IL); **Adi Levin**, Nes Tziona (IL); **Ofer Saphier**, Rechovot (IL); **Maayan Moshe**, Ra'anana (IL)

(73) Assignee: **Align Technology, Inc.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 19 days.

(21) Appl. No.: **14/825,173**

(22) Filed: **Aug. 13, 2015**

(65) **Prior Publication Data**

US 2016/0045291 A1 Feb. 18, 2016

Related U.S. Application Data

(60) Provisional application No. 62/037,778, filed on Aug. 15, 2014.

(51) **Int. Cl.**
G01B 11/24 (2006.01)
A61C 9/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61C 9/0066*** (2013.01); ***G01B 11/24*** (2013.01); ***G02B 23/2446*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC A61C 9/0066; A61C 9/0053; G01B 11/24; G02B 23/2446; G02B 23/2461; G02B 23/26; G02B 27/0025
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,737,084	A	4/1998	Ishihara
6,697,164	B1	2/2004	Babayoff et al.

(Continued)

FOREIGN PATENT DOCUMENTS

DE	102005043627	A1	3/2007
EP	2437027	A2	4/2012

(Continued)

OTHER PUBLICATIONS

Tiziani, H. J. et al. "Confocal principle for macro- and microscopic surface and defect analysis," Optical Engineering, Jan. 1, 2000, pp. 32-39, vol. 39(1), Society of Photo-Optical Instrumentation Engineers.

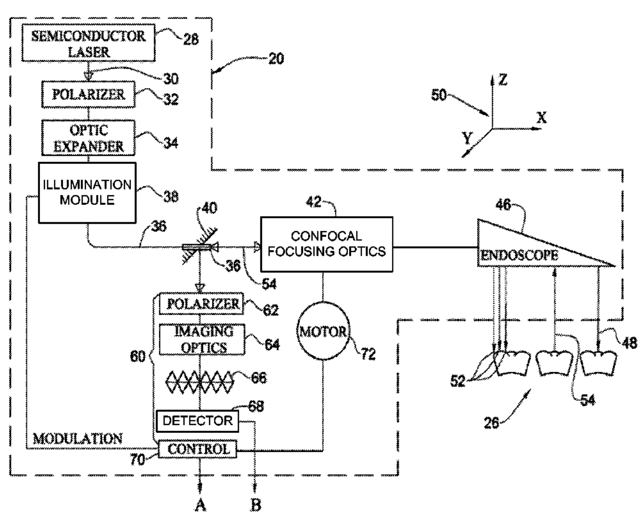
(Continued)

Primary Examiner — Tri T Ton
(74) *Attorney, Agent, or Firm* — Lowenstein Sandler LLP

(57) **ABSTRACT**

A confocal imaging apparatus includes an illumination module to generate an array of light beams. Focusing optics perform confocal focusing of an array of light beams onto a non-flat focal surface and direct the array of light beams toward a three dimensional object to be imaged. A translation mechanism adjusts a location of at least one lens to displace the non-flat focal surface along an imaging axis. A detector measures intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics. Intensities of the array of returning light beams are measured for locations of the at least one lens for determination of positions on the imaging axis of points of the three dimensional object. Detected positions of one or more points are adjusted to compensate for the non-flat focal surface.

12 Claims, 13 Drawing Sheets



(51) **Int. Cl.**
G02B 23/24 (2006.01)
G02B 27/00 (2006.01)
G02B 23/26 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 23/2461*** (2013.01); ***G02B 23/26*** (2013.01); ***G02B 27/0025*** (2013.01)

(58) **Field of Classification Search**
USPC 356/601–640
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

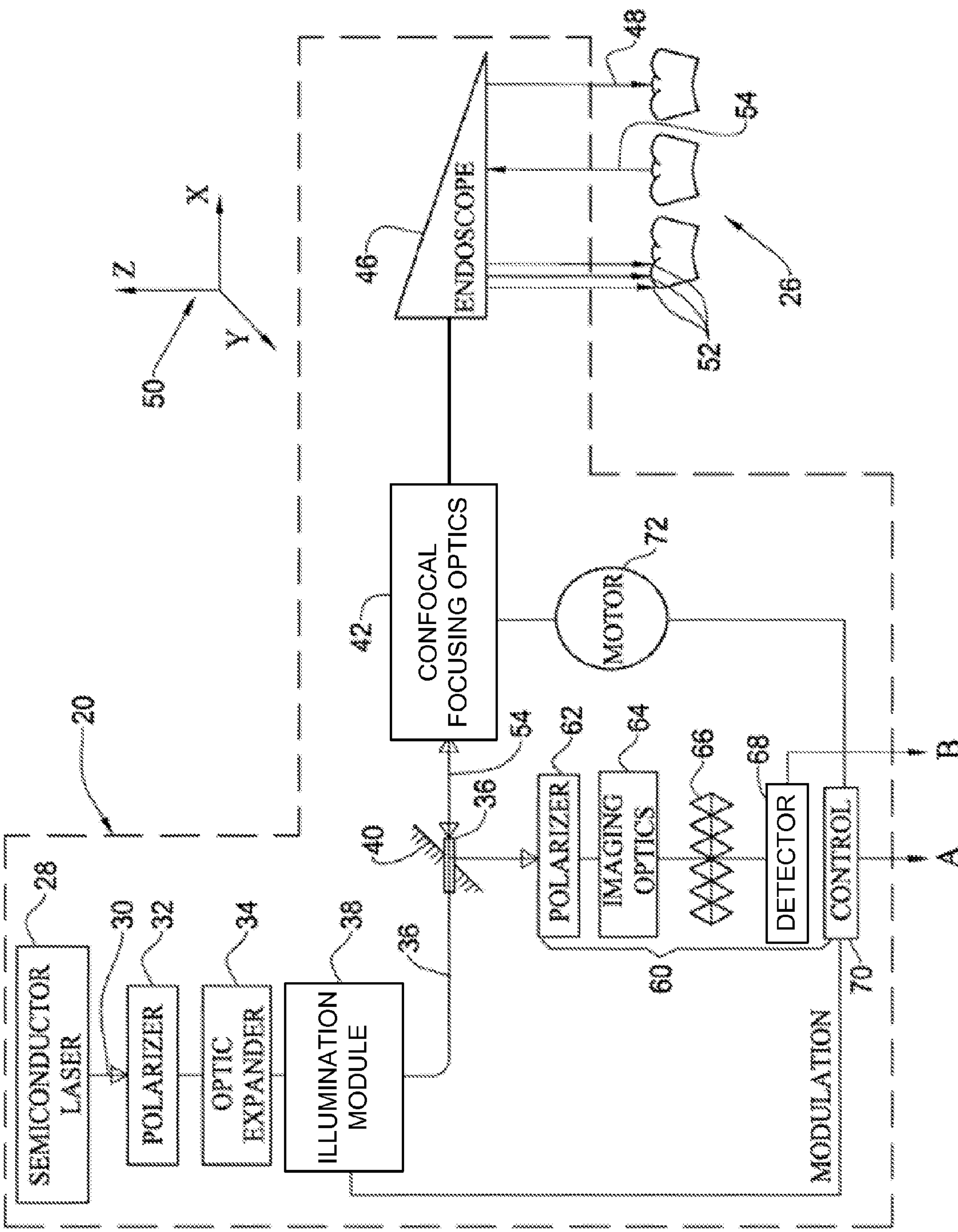
7,092,107	B2	8/2006	Babayoff et al.
8,310,683	B2	11/2012	Babayoff et al.
8,363,228	B2	1/2013	Babayoff

FOREIGN PATENT DOCUMENTS

WO	00/08415	A1	2/2000
WO	2015/015289	A2	2/2015

OTHER PUBLICATIONS

International Search Report and Written Opinion for PCT Application No. PCT/IB2015/001400 mailed Feb. 9, 2016.



SEMICONDUCTOR LASER
POLARIZER
OPTIC EXPANDER
ILLUMINATION MODULE
CONFOCAL FOCUSING OPTICS
ENDOSCOPE
MOTOR
POLARIZER
IMAGING OPTICS
DETECTOR
CONTROL
MODULATION
X
Y
Z
A
B
20
26
28
30
32
34
36
38
40
42
46
48
50
52
54
60
62
64
66
68
70
72

FIG. 1A

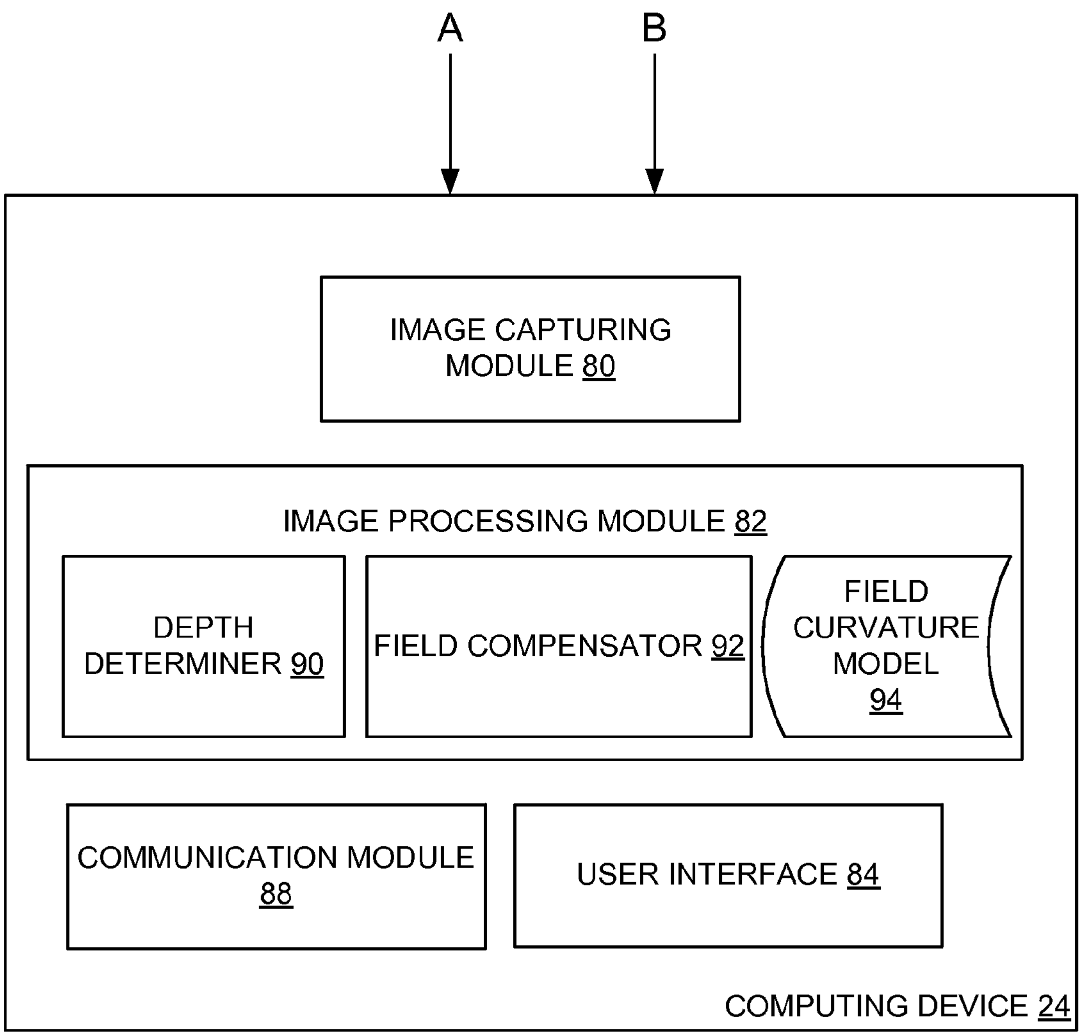

A
B
IMAGE CAPTURING MODULE 80
IMAGE PROCESSING MODULE 82
DEPTH DETERMINER 90
FIELD COMPENSATOR 92
FIELD CURVATURE MODEL 94
COMMUNICATION MODULE 88
USER INTERFACE 84
COMPUTING DEVICE 24

FIG. 1B

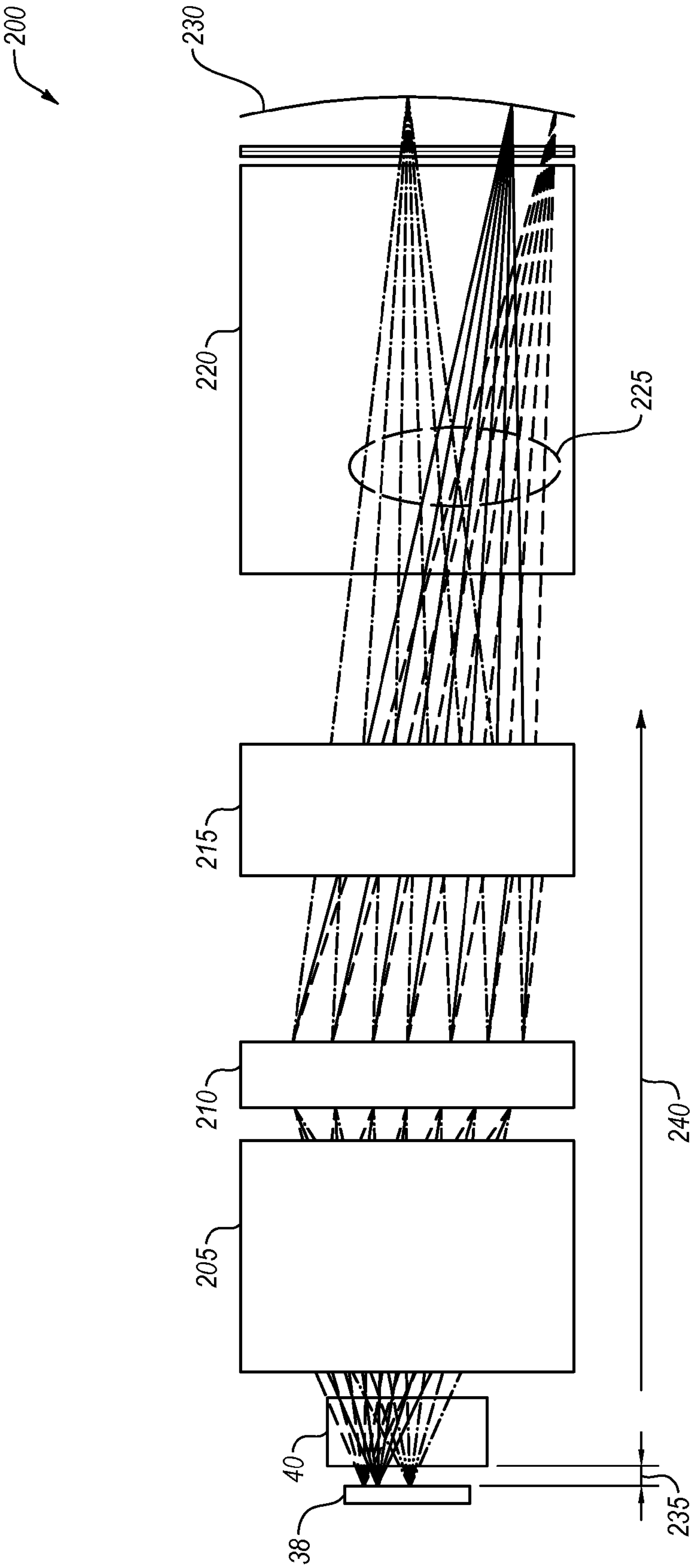


FIG. 2A

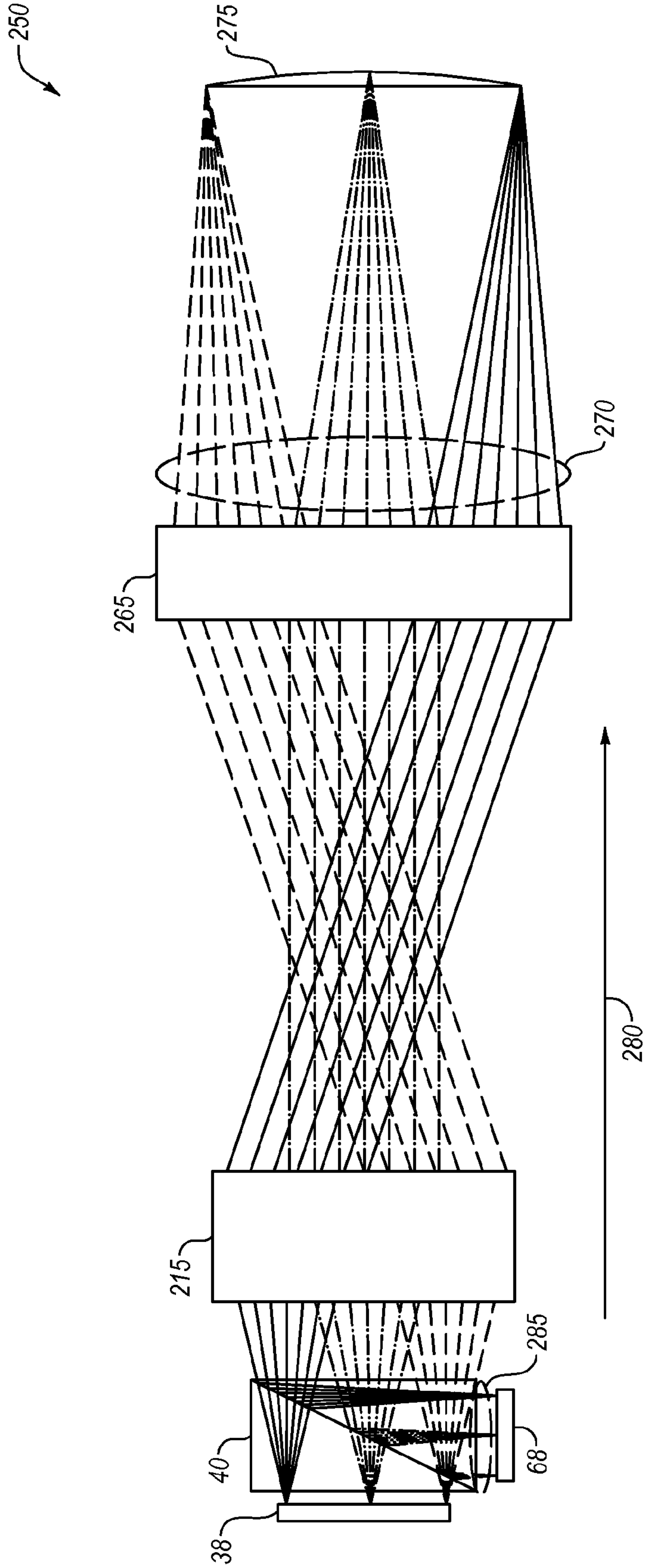


FIG. 2B

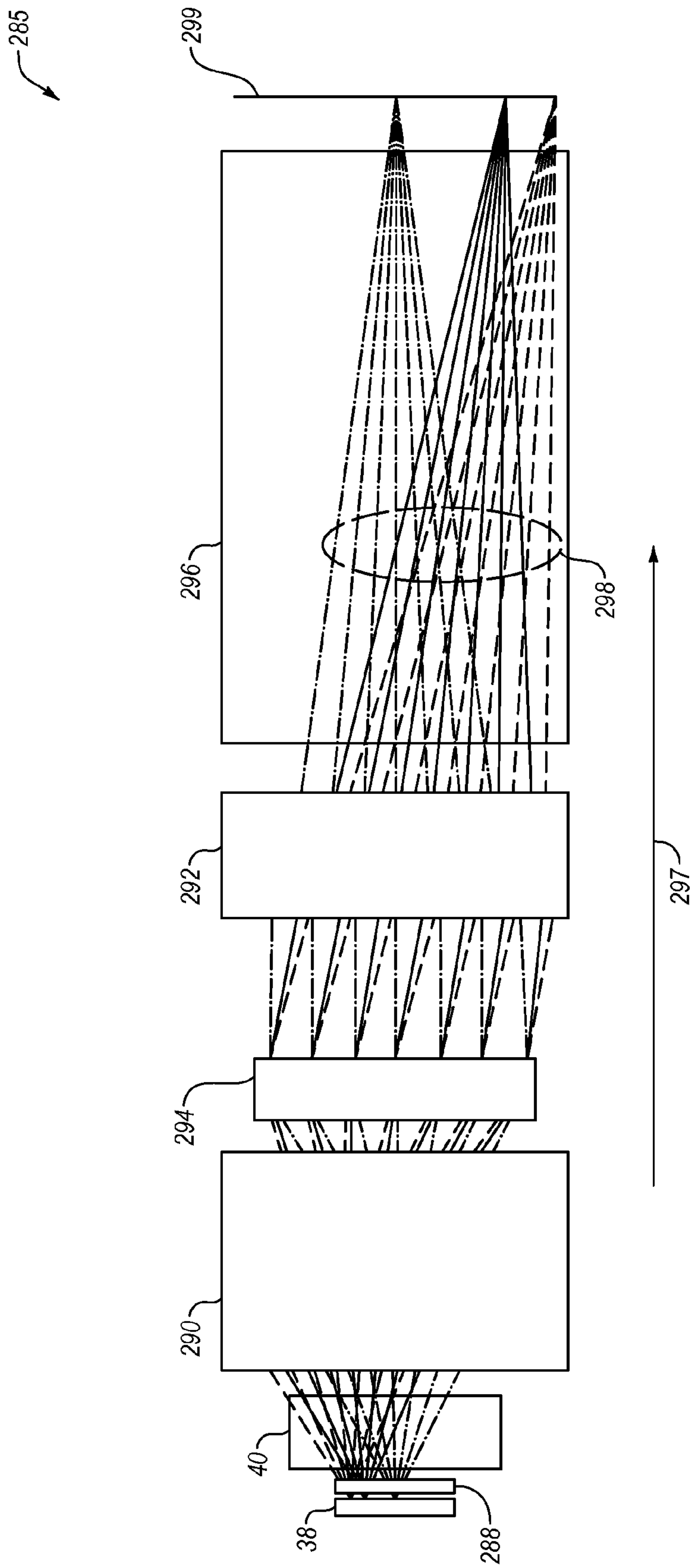
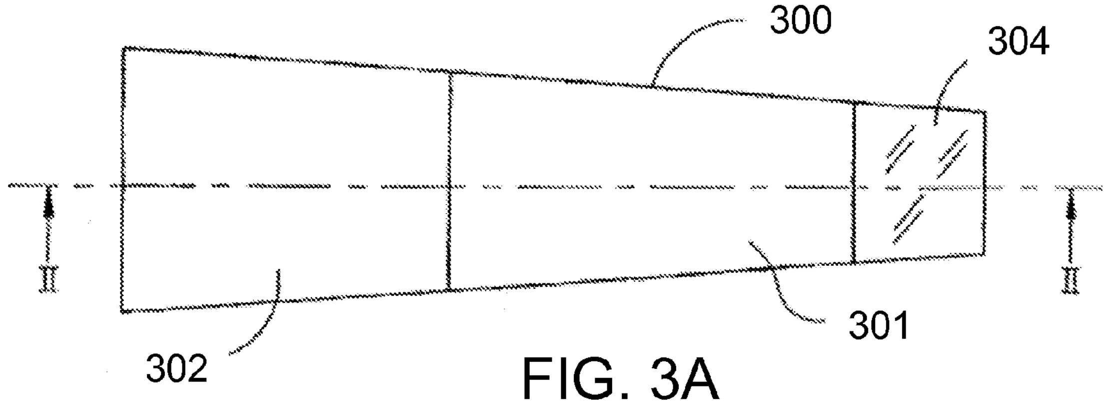
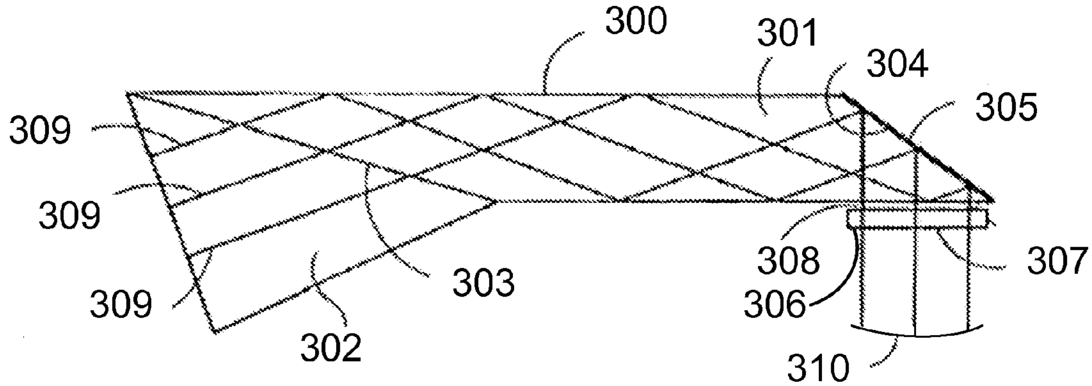


FIG. 2C



300
304
II
II
301
302

FIG. 3A



300
301
304
305
309
309
303
308
307
306
309
302
310

FIG. 3B

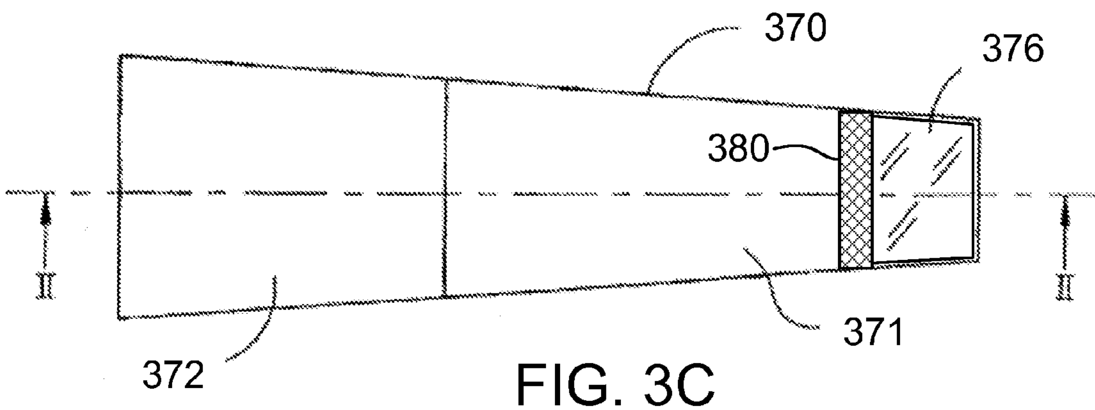


FIG. 3C

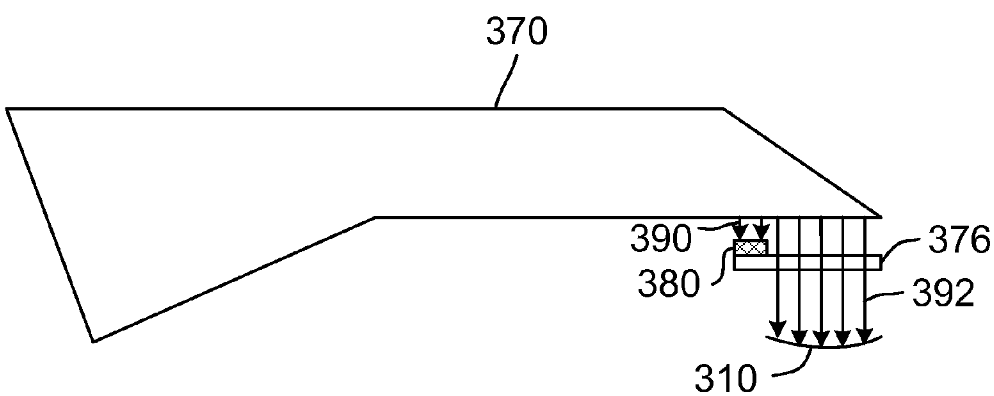


FIG. 3D

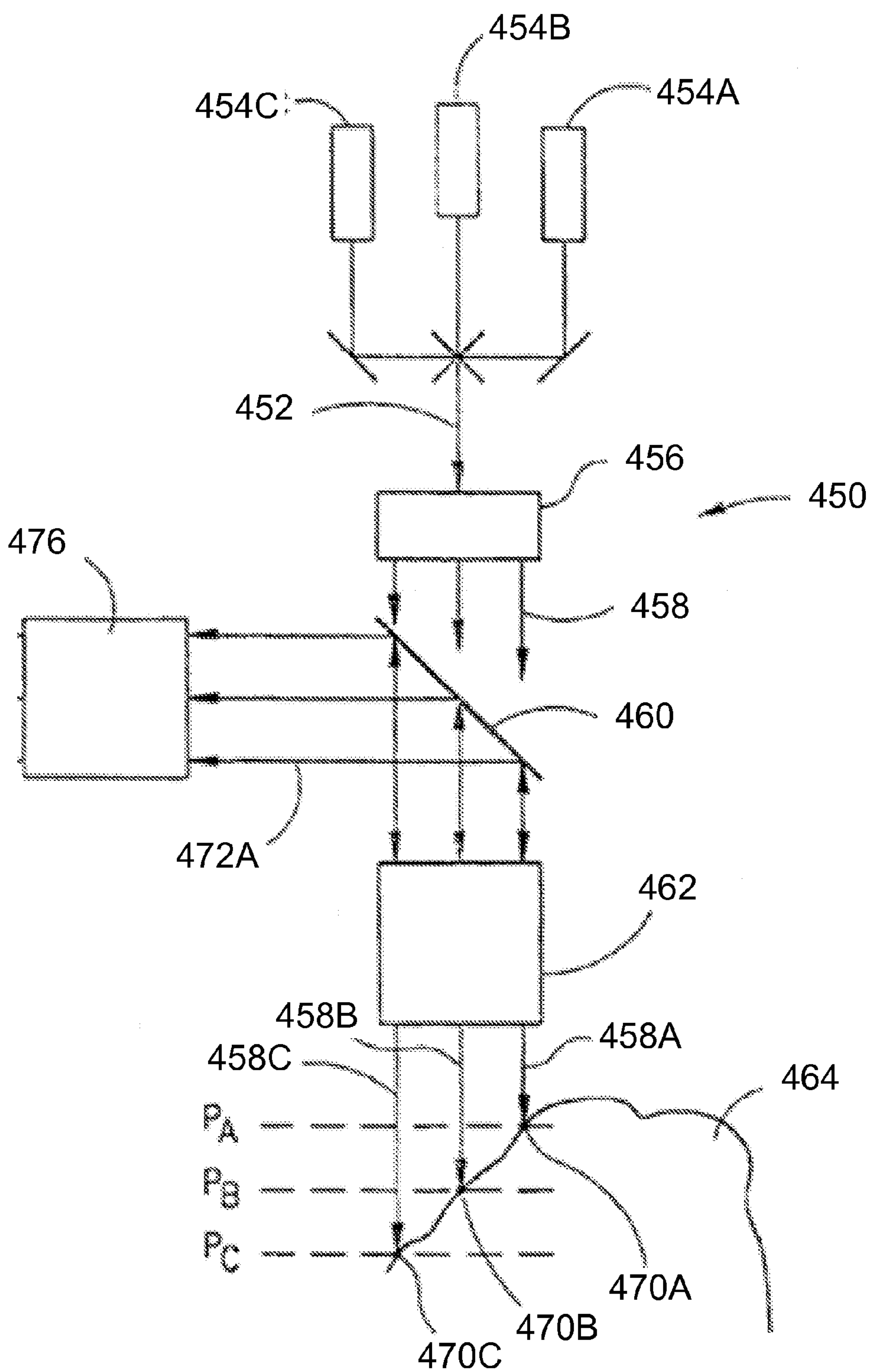

454B
454C
454A
452
456
450
476
458
460
472A
462
458B
458C
458A
464
P_A
P_B
P_C
470A
470B
470C

FIG. 4

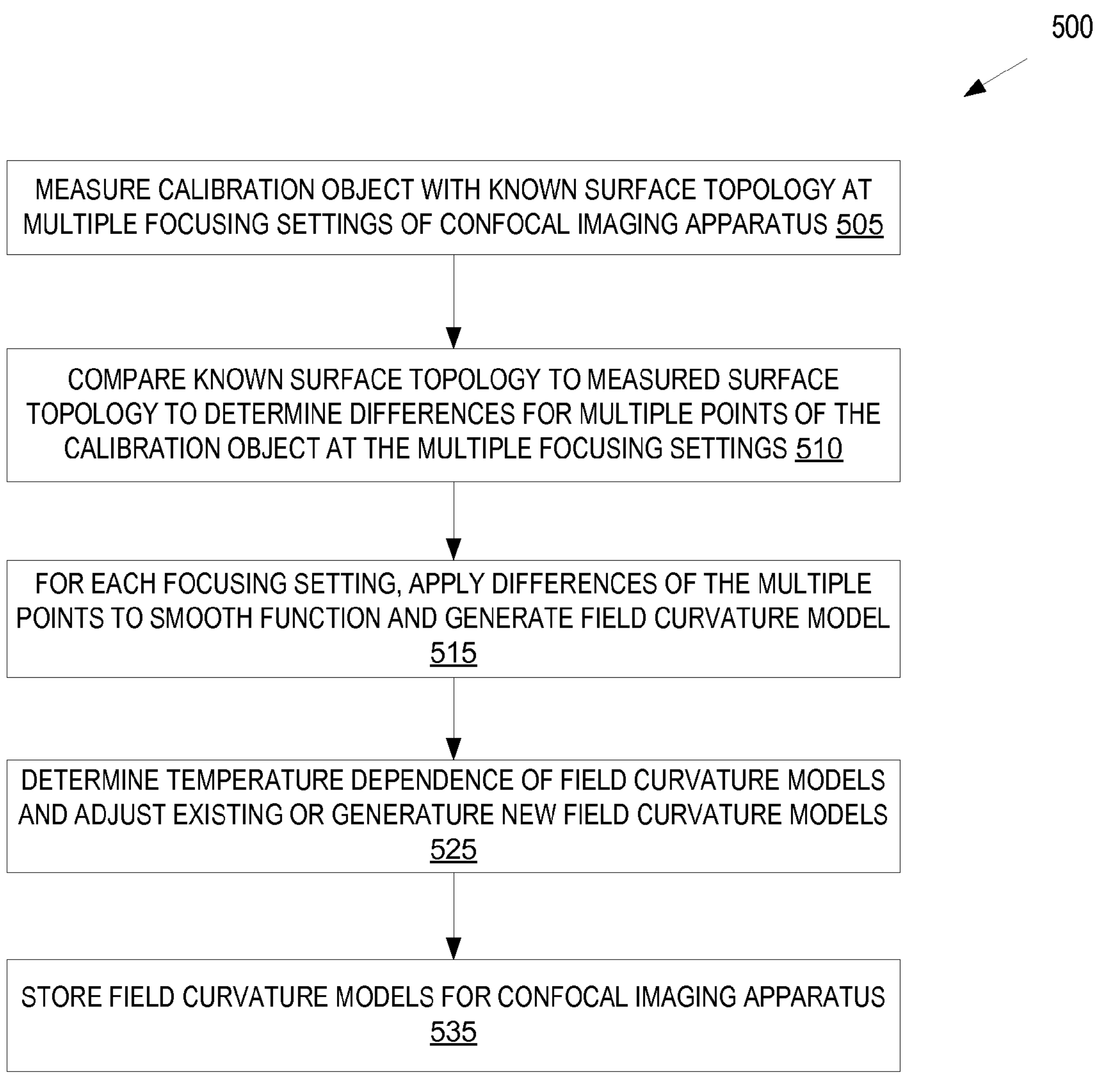

500
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 505
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 510
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SMOOTH FUNCTION AND GENERATE FIELD CURVATURE MODEL 515
DETERMINE TEMPERATURE DEPENDENCE OF FIELD CURVATURE MODELS AND ADJUST EXISTING OR GENERATURE NEW FIELD CURVATURE MODELS 525
STORE FIELD CURVATURE MODELS FOR CONFOCAL IMAGING APPARATUS 535

FIG. 5A

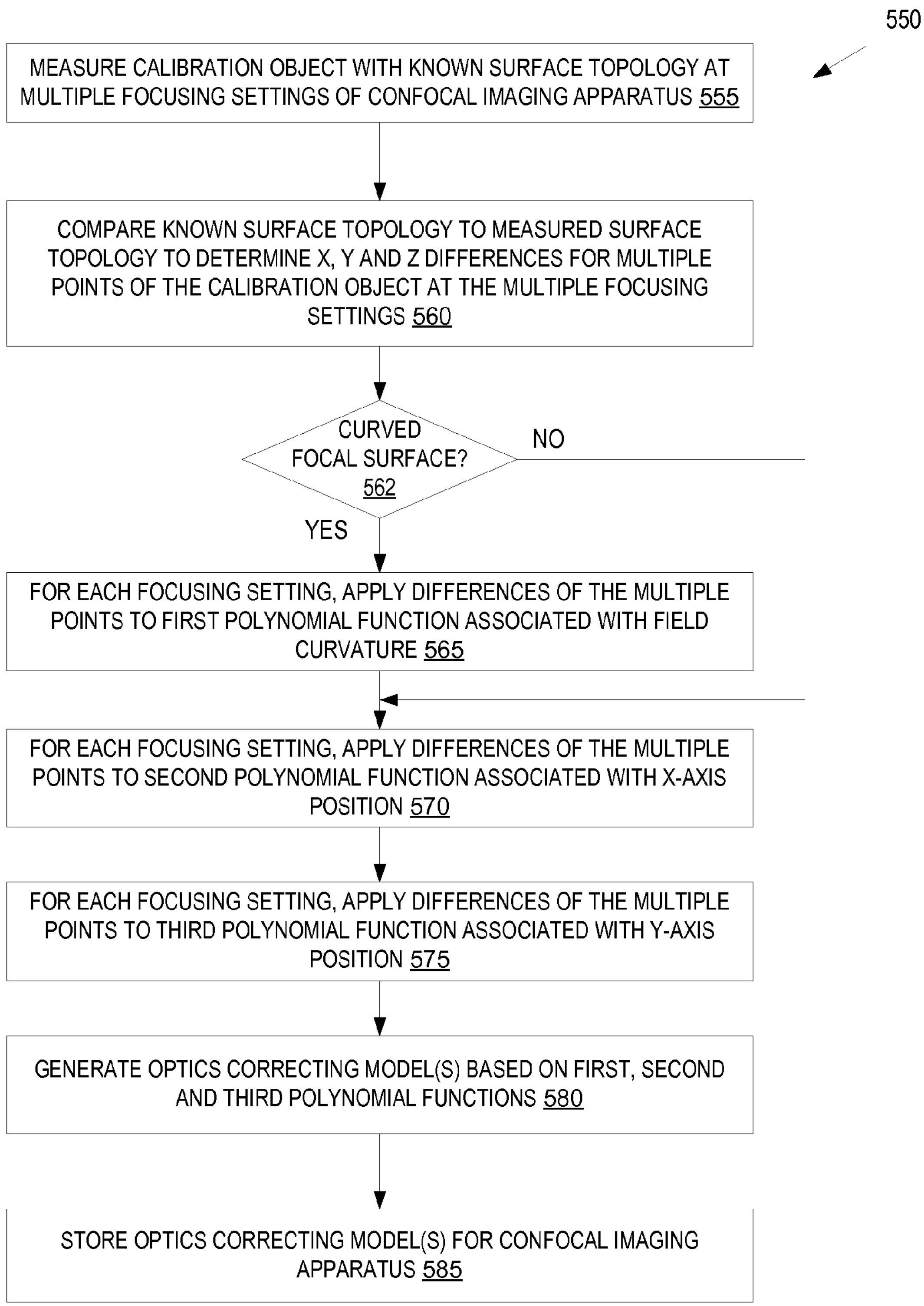

550
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 555
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE X, Y AND Z DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 560
CURVED FOCAL SURFACE? 562
NO
YES
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO FIRST POLYNOMIAL FUNCTION ASSOCIATED WITH FIELD CURVATURE 565
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SECOND POLYNOMIAL FUNCTION ASSOCIATED WITH X-AXIS POSITION 570
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO THIRD POLYNOMIAL FUNCTION ASSOCIATED WITH Y-AXIS POSITION 575
GENERATE OPTICS CORRECTING MODEL(S) BASED ON FIRST, SECOND AND THIRD POLYNOMIAL FUNCTIONS 580
STORE OPTICS CORRECTING MODEL(S) FOR CONFOCAL IMAGING APPARATUS 585

FIG. 5B

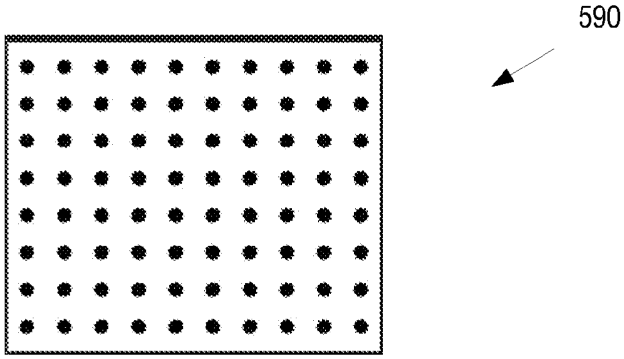


FIG. 5C

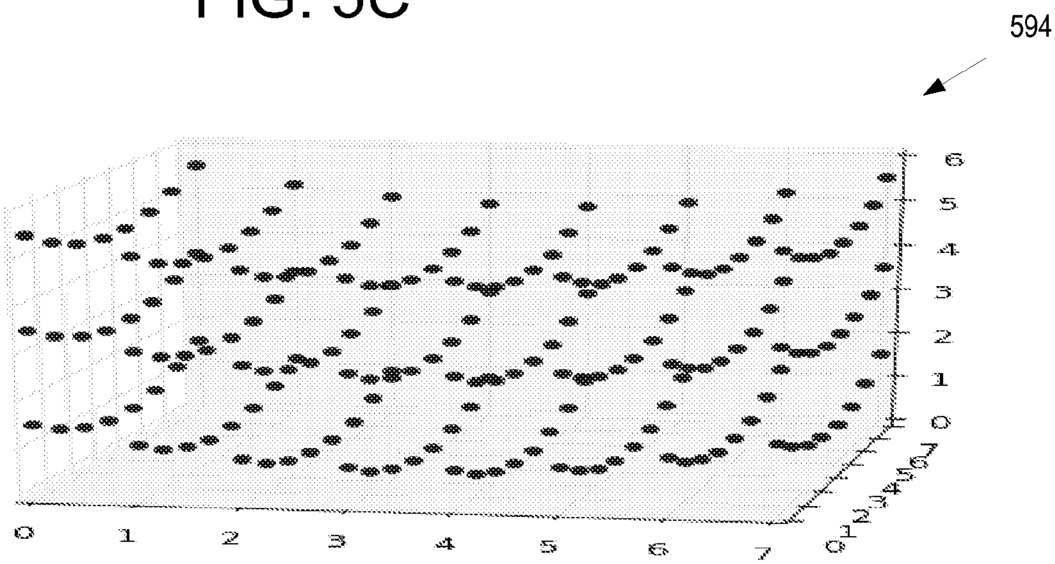


FIG. 5D

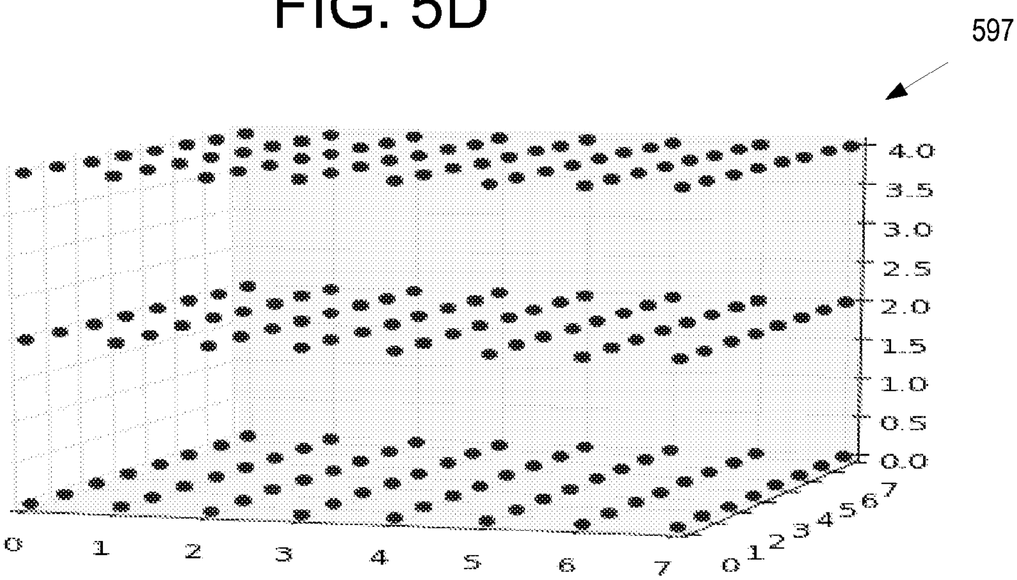


FIG. 5E

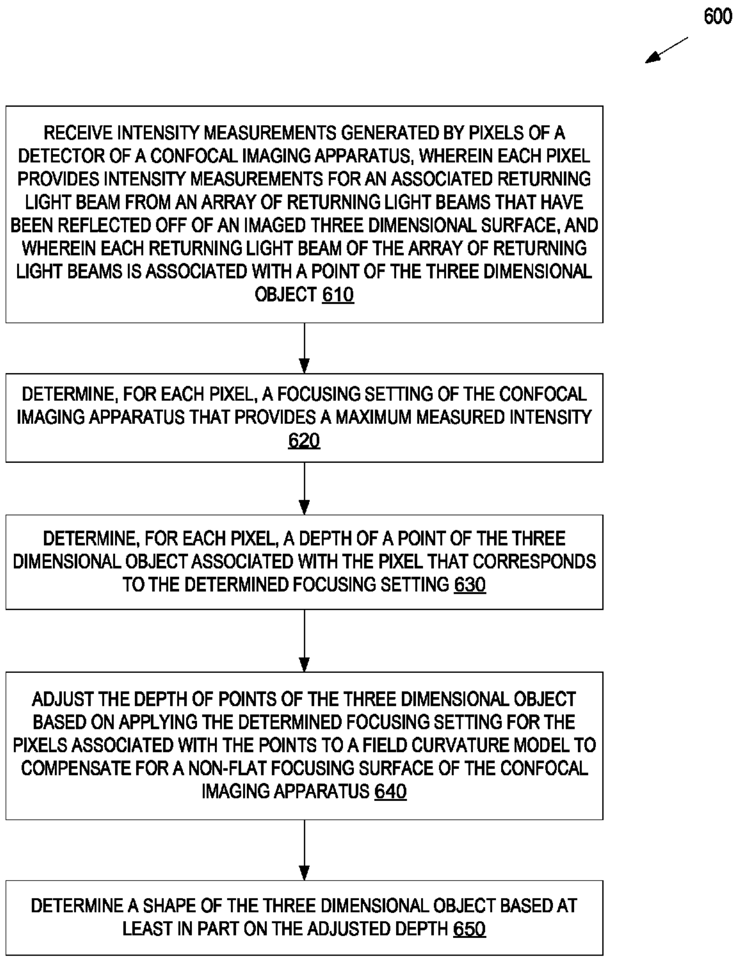

600
RECEIVE INTENSITY MEASUREMENTS GENERATED BY PIXELS OF A DETECTOR OF A CONFOCAL IMAGING APPARATUS, WHEREIN EACH PIXEL PROVIDES INTENSITY MEASUREMENTS FOR AN ASSOCIATED RETURNING LIGHT BEAM FROM AN ARRAY OF RETURNING LIGHT BEAMS THAT HAVE BEEN REFLECTED OFF OF AN IMAGED THREE DIMENSIONAL SURFACE, AND WHEREIN EACH RETURNING LIGHT BEAM OF THE ARRAY OF RETURNING LIGHT BEAMS IS ASSOCIATED WITH A POINT OF THE THREE DIMENSIONAL OBJECT 610
DETERMINE, FOR EACH PIXEL, A FOCUSING SETTING OF THE CONFOCAL IMAGING APPARATUS THAT PROVIDES A MAXIMUM MEASURED INTENSITY 620
DETERMINE, FOR EACH PIXEL, A DEPTH OF A POINT OF THE THREE DIMENSIONAL OBJECT ASSOCIATED WITH THE PIXEL THAT CORRESPONDS TO THE DETERMINED FOCUSING SETTING 630
ADJUST THE DEPTH OF POINTS OF THE THREE DIMENSIONAL OBJECT BASED ON APPLYING THE DETERMINED FOCUSING SETTING FOR THE PIXELS ASSOCIATED WITH THE POINTS TO A FIELD CURVATURE MODEL TO COMPENSATE FOR A NON-FLAT FOCUSING SURFACE OF THE CONFOCAL IMAGING APPARATUS 640
DETERMINE A SHAPE OF THE THREE DIMENSIONAL OBJECT BASED AT LEAST IN PART ON THE ADJUSTED DEPTH 650

FIG. 6

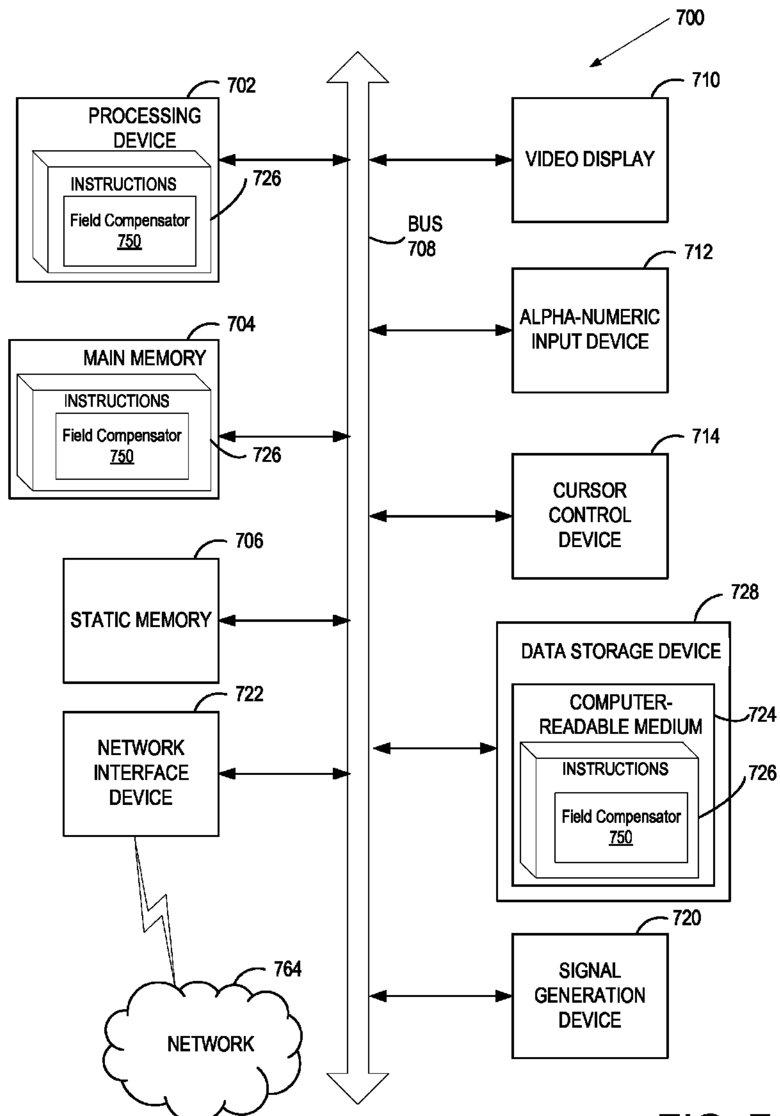

700
702
PROCESSING DEVICE
INSTRUCTIONS
Field Compensator 750
726
BUS 708
710
VIDEO DISPLAY
712
ALPHA-NUMERIC INPUT DEVICE
704
MAIN MEMORY
INSTRUCTIONS
Field Compensator 750
726
714
CURSOR CONTROL DEVICE
706
STATIC MEMORY
728
DATA STORAGE DEVICE
COMPUTER-READABLE MEDIUM
724
INSTRUCTIONS
Field Compensator 750
726
722
NETWORK INTERFACE DEVICE
720
SIGNAL GENERATION DEVICE
764
NETWORK

FIG. 7

CONFOCAL IMAGING APPARATUS WITH CURVED FOCAL SURFACE

RELATED APPLICATIONS

This patent application claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Application No. 62/037,778, filed Aug. 15, 2014.

TECHNICAL FIELD

Embodiments of the present invention relate to the field of imaging and, in particular, to a system and method for performing confocal imaging of a three dimensional surface.

BACKGROUND

A great variety of methods and systems have been developed for direct optical measurement of teeth and the subsequent automatic manufacture of dentures. The term "direct optical measurement" signifies surveying of teeth in the oral cavity of a patient. This facilitates the obtainment of digital constructional data necessary for the computer-assisted design (CAD) or computer-assisted manufacture (CAM) of tooth replacements without having to make any cast impressions of the teeth. Such systems typically include an optical probe coupled to an optical pick-up or receiver such as charge coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) sensor and a processor implementing a suitable image processing technique to design and fabricate virtually the desired product.

One type of system that performs intra-oral scans is a system that uses confocal imaging to image a three dimensional surface. Such systems that use confocal imaging typically include field lenses to flatten an imaging field and enable flat focal planes for emitted light beams. Such flat focal planes ensure that the surface topology of scanned three dimensional surfaces is accurate. However, the field lenses are diverging lenses that open the rays of the light beams. This causes the optics of the confocal imaging apparatus to be enlarged. Additionally, the field lenses should be aligned to ensure accuracy. Such alignment can be a time consuming and challenging process.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

FIG. **1**A illustrates a functional block diagram of a confocal imaging apparatus according to one embodiment.

FIG. **1**B illustrates a block diagram of a computing device that connects to a confocal imaging apparatus, in accordance with one embodiment.

FIG. **2**A illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment.

FIG. **2**B illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with another embodiment.

FIG. **2**C illustrates optics of a confocal imaging apparatus with a field lens for which changes in a focusing setting cause changes in magnification, in accordance with another embodiment.

FIG. **3**A is a top view of a probing member of a confocal imaging apparatus that includes a prism, in accordance with an embodiment of the invention.

FIG. **3**B is a longitudinal cross-section through line II-II of the probing member in FIG. **3**A.

FIG. **3**C is a view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. **3**D is a side view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. **4** is a schematic illustration of optics of a confocal imaging apparatus, in accordance with one embodiment.

FIG. **5**A is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface.

FIG. **5**B is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification.

FIG. **5**C illustrates one example calibration object, in accordance with one embodiment.

FIG. **5**D illustrates a chart showing a distribution of points of a calibration object as measured by a confocal imaging apparatus, in accordance with one embodiment.

FIG. **5**E illustrates a chart showing a distribution of points in a world coordinate system, in accordance with one embodiment.

FIG. **6** is a flow chart showing one embodiment of a method for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model calibrated to a confocal imaging apparatus.

FIG. **7** illustrates a block diagram of an example computing device, in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

Described herein is a confocal imaging apparatus having a non-flat focal surface. The non-flat focal surface may be caused by the optics of the confocal imaging apparatus lacking a field lens. As is discussed in greater detail below, the lack of a field lens in the confocal imaging apparatus introduces challenges but also provides numerous advantages. For example, a confocal imaging apparatus without a field lens is smaller, lighter and easier to manufacture than a confocal imaging apparatus having a field lens. Embodiments discussed herein show how to overcome the challenges in designing and using a confocal imaging apparatus lacking a field lens.

Also described herein is a large field confocal imaging apparatus having focusing optics that change a magnification of a focal surface with changes in a focusing setting. As is discussed in greater detail below, the change in magnification introduces challenges that are overcome in embodiments.

In one embodiment, a confocal imaging apparatus includes an illumination module to generate an array of light beams. Focusing optics of the confocal imaging apparatus perform confocal focusing of an array of light beams onto a non-flat focal surface and direct the array of light beams toward a three dimensional object to be imaged. A translation mechanism of the confocal imaging apparatus adjusts a location of at least one lens to displace the non-flat focal surface along an imaging axis. A detector of the confocal imaging apparatus measures intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics. Intensities of the array of returning light beams are measured for locations of the at least one lens for determination of positions on the imaging axis of points of the three dimensional object. Detected positions of one or more points are

adjusted to compensate for the non-flat focal surface. Thus, an object may be accurately imaged despite the non-flat focal surface of the confocal imaging apparatus.

FIG. **1**A illustrates a functional block diagram of a confocal imaging apparatus **20** according to one embodiment. FIG. **1**B illustrates a block diagram of a computing device **24** that connects to the confocal imaging apparatus **20**. Together, the confocal imaging apparatus **20** and computing device **24** may form a system for generating three dimensional images of scanned objects. The computing device **24** may be connected to the confocal imaging apparatus **20** directly or indirectly and via a wired or wireless connection. For example, the confocal imaging apparatus **20** may include a network interface controller (NIC) capable of communicating via Wi-Fi, via third generation (3G) or fourth generation (4G) telecommunications protocols (e.g., global system for mobile communications (GSM), long term evolution (LTE), Wi-Max, code division multiple access (CDMA), etc.), via Bluetooth, via Zigbee, or via other wireless protocols. Alternatively, or additionally, confocal imaging apparatus may include an Ethernet network interface controller (NIC), a universal serial bus (USB) port, or other wired port. The NIC or port may connect the confocal imaging apparatus to the computing device via a local area network (LAN). Alternatively, the confocal imaging apparatus **20** may connect to a wide area network (WAN) such as the Internet, and may connect to the computing device **24** via the WAN. In an alternative embodiment, confocal imaging apparatus **20** is connected directly to the computing device (e.g., via a direct wired or wireless connection). In one embodiment, the computing device **24** is a component of the confocal imaging apparatus **20**.

Referring now to FIG. **1**A, in one embodiment confocal imaging apparatus **20** includes a semiconductor laser unit **28** that emits a focused light beam, as represented by arrow **30**. The light beam **30** passes through a polarizer **32**. Polarizer **32** polarizes the light beam passing through polarizer **32**. Alternatively, polarizer **32** may be omitted in some embodiments. The light beam then enters into an optic expander **34** that improves a numerical aperture of the light beam **30**. The light beam **30** then passes through an illumination module **38**, which splits the light beam **30** into an array of incident light beams **36**, represented here, for ease of illustration, by a single line. The illumination module **38** may be, for example, a grating or a micro lens array that splits the light beam **30** into an array of light beams **36**. In one embodiment, the array of light beams **36** is an array of telecentric light beams. Alternatively, the array of light beams may not be telecentric.

The confocal imaging apparatus **20** further includes a unidirectional mirror or beam splitter (e.g., a polarizing beam splitter) **40** that passes the array of light beams **36**. A unidirectional mirror **40** allows transfer of light from the semiconductor laser **28** through to downstream optics, but reflects light travelling in the opposite direction. A polarizing beam splitter allows transfer of light beams having a particular polarization and reflects light beams having a different (e.g., opposite) polarization. In one embodiment, the unidirectional mirror or beam splitter **40** has a small central aperture. The small central aperture may improve a measurement accuracy of the confocal imaging apparatus **20**. In one embodiment, as a result of a structure of the unidirectional mirror or beam splitter **40**, the array of light beams will yield a light annulus on an illuminated area of an imaged object as long as the area is not in focus. Moreover, the annulus will become a completely illuminated spot once in focus. This ensures that a difference between measured intensities of out-of focus points and in-focus points will be larger.

Along an optical path of the array of light beams after the unidirectional mirror or beam splitter **40** are confocal focusing optics **42**, and an endoscopic probing member **46**. Additionally, a quarter wave plate may be disposed along the optical path after the unidirectional mirror or beam splitter **40** to introduce a certain polarization to the array of light beams. In some embodiments this may ensure that reflected light beams will not be passed through the unidirectional mirror or beam splitter **40**. Confocal focusing optics **42** may additionally include relay optics (not shown). Confocal focusing optics **42** may or may not maintain the same magnification of an image over a wide range of distances in the Z direction, wherein the Z direction is a direction of beam propagation (e.g., the Z direction corresponds to an imaging axis that is aligned with an optical path of the array of light beams **36**). The relay optics enable the confocal imaging apparatus **20** to maintain a certain numerical aperture for propagation of the array of light beams **36**. The confocal focusing optics **42** and endoscopic probing member **46** are discussed in greater detail with reference to FIGS. **2**A-**2**C.

The endoscopic probing member **46** may include a rigid, light-transmitting medium, which may be a hollow object defining within it a light transmission path or an object made of a light transmitting material, e.g. a glass body or tube. In one embodiment, the endoscopic probing member **46** include a prism such as a folding prism. At its end, the endoscopic probing member **46** may include a mirror of the kind ensuring a total internal reflection. Thus, the mirror may direct the array of light beams towards a teeth segment **26** or other object. The endoscope probing member **46** thus emits array of light beams **48**, which impinge on to surfaces of the teeth section **26**.

The array of light beams **48** are arranged in an X-Y plane, in the Cartesian frame **50**, propagating along the Z axis. As the surface on which the incident light beams hits is an uneven surface, illuminated spots **52** are displaced from one another along the Z axis, at different (X_i, Y_i) locations. Thus, while a spot at one location may be in focus of the confocal focusing optics **42**, spots at other locations may be out-of-focus. Therefore, the light intensity of returned light beams of the focused spots will be at its peak, while the light intensity at other spots will be off peak. Thus, for each illuminated spot, multiple measurements of light intensity are made at different positions along the Z-axis. For each of such (X_i, Y_i) location, the derivative of the intensity over distance (Z) may be made, with the Z_i yielding maximum derivative, Z_0, being the in-focus distance. As pointed out above, the incident light from the array of light beams **48** forms a light disk on the surface when out of focus and a complete light spot when in focus. Thus, the distance derivative will be larger when approaching in-focus position, increasing accuracy of the measurement.

The light scattered from each of the light spots includes a beam travelling initially in the Z axis along the opposite direction of the optical path traveled by the array of light beams **48**. Each returned light beam in an array of returning light beams **54** corresponds to one of the incident light beams in array of light beams **36**. Given the asymmetrical properties of unidirectional mirror or beam splitter **40**, the returned light beams are reflected in the direction of detection optics **60**.

The detection optics **60** may include a polarizer **62** that has a plane of preferred polarization oriented normal to the

plane polarization of polarizer **32**. Alternatively, polarizer **32** and polarizer **62** may be omitted in some embodiments. The array of returning light beams **54** may pass through imaging optics **64** in one embodiment. The imaging optics **64** may be one or more lenses. Alternatively, the detection optics **60** may not include imaging optics **64**. In one embodiment, the array of returning light beams **54** further passes through a matrix **66**, which may be an array of pinholes. Alternatively, no matrix **66** is used in some embodiments. The array of returning light beams **54** are then directed onto a detector **68**.

The detector **68** is an image sensor having a matrix of sensing elements each representing a pixel of the image. If matrix **66** is used, then each pixel further corresponds to one pinhole of matrix **66**. In one embodiment, the detector is a charge coupled device (CCD) sensor. In one embodiment, the detector is a complementary metal-oxide semiconductor (CMOS) type image sensor. Other types of image sensors may also be used for detector **68**. The detector **68** detects light intensity at each pixel.

In one embodiment, detector **68** provides data to computing device **24**. Thus, each light intensity measured in each of the sensing elements of the detector **68**, is then captured and analyzed, in a manner to be described below, by processor **24**.

Confocal imaging apparatus **20** further includes a control module **70** connected both to semiconductor laser **28** and a motor **72**, voice coil or other translation mechanism. In one embodiment, control module **70** is or includes a field programmable gate array (FPGA) configured to perform control operations. Motor **72** is linked to confocal focusing optics **42** for changing a focusing setting of confocal focusing optics **42**. This may adjust the relative location of an imaginary non-flat focal surface of confocal focusing optics **42** along the Z-axis (e.g., in the imaging axis). Control module **70** may induce motor **72** to axially displace (change a location of) one or more lenses of the confocal focusing optics **42** to change the focal depth of the imaginary non-flat focal surface. In one embodiment, motor **72** or confocal imaging apparatus **20** includes an encoder (not shown) that accurately measures a position of one or more lenses of the confocal focusing optics **42**. The encoder may include a sensor paired to a scale that encodes a linear position. The encoder may output a linear position of the one or more lenses of the confocal focusing optics **42**. The encoder may be an optical encoder, a magnetic encoder, an inductive encoder, a capacitive encoder, an eddy current encoder, and so on. After receipt of feedback that the location of the one or more lenses has changed, control module **70** may induce laser **28** to generate a light pulse. Control unit **70** may additionally synchronize image-capturing module **80** from FIG. **1**B to receive and/or store data representative of the light intensity from each of the sensing elements at the particular location of the one or more lenses (and thus of the focal depth of the imaginary non-flat focal surface). In subsequent sequences, the location of the one or more lenses (and thus the focal depth) will change in the same manner and the data capturing will continue over a wide focal range of confocal focusing optics **42**.

Referring now to FIG. **1**B, image capturing module **80** may capture images responsive to receiving image capture commands from the control unit **70**. The captured images may be associated with a particular focusing setting (e.g., a particular location of one or more lenses in the confocal focusing optics as output by the encoder). Image processing module **82** then processes captured images captured over multiple different focusing settings. Image processing module **82** includes a depth determiner **90** and a field compensator **92** for processing image data.

Depth determiner **90** determines the relative intensity in each pixel over the entire range of focal settings of confocal focusing optics **42** from received image data. Once a certain light spot associated with a particular pixel is in focus, the measured intensity will be maximal for that pixel. Thus, by determining the Z_i corresponding to the maximal light intensity or by determining the maximum displacement derivative of the light intensity, for each pixel, the relative position of each light spot along the Z axis can be determined for each pixel. Thus, data representative of the three-dimensional pattern of a surface in the teeth segment **26** or other three dimensional object can be obtained.

In embodiments, the confocal focusing optics **42** of confocal imaging apparatus **20** lack field lenses. The purpose of the field lens is to flatten a focal field and thus produce a flat focal plane for the array of light beams. For confocal imaging apparatuses with field lenses, each light beam from the array of light beams focuses on the same flat focal plane. However, without such field lenses the array of light beams focus on an imaginary non-flat focal surface (e.g., on a curved focal surface). This causes the Z axis information that depth determiner **90** computes to be distorted for many pixels.

Field compensator **92** compensates for the curved field caused by the lack of a field lens. Field compensator **92** may also compensate for changes in a position of the curved focal surface caused by temperature and/or for magnification changes caused by changes in a focusing setting. Field compensator **92** applies a field curvature model **94** and/or other optics compensation model (not shown) to each Z axis measurement of each pixel to correct for field curvature, temperature and/or magnification changes. In one embodiment, a different field curvature model **94** (or other optics compensation model) is applied for each focusing setting of the confocal imaging apparatus **20**. This is because the amount of field curvature and/or magnification may change with changes in the focusing setting. Alternatively, a single field curvature model **94** (or other optics compensation model) may account for the changes in the field curvature caused by changes in the focusing setting and/or for changes in magnification caused by changes in the focusing setting. For each combination of an X,Y pixel location and a focusing setting (e.g., a z-axis position of one or more lenses of the focusing optics), a particular depth adjustment may be applied based on the field curvature model or models. Additionally, an X location adjustment and/or a Y location adjustment bay be applied based on the field curvature model and/or other optics compensation model. In one embodiment, for each combination of an X,Y pixel location, a focusing setting, and a temperature reading or a z-axis position of a measured element whose position changes with changes in temperature, a particular depth adjustment may be applied based on the field curvature model or models. The adjusted depth (z-axis) values represent the actual z-axis values of the imaged surface.

A three-dimensional representation may be constructed based on the corrected measurement data and displayed via a user interface **84**. The user interface **84** may be a graphical user interface that includes controls for manipulating a display of the three-dimensional representation (e.g., viewing from different angles, zooming-in or out, etc.). In addition, data representative of the surface topology of the scanned object may be transmitted to remote devices by a

communication module **88** for further processing or use (e.g., to generate a three dimensional virtual model of the scanned object).

By capturing, in this manner, an image from two or more angular locations around the structure, e.g. in the case of a teeth segment from the buccal direction, from the lingual direction and optionally from above the teeth, an accurate three-dimensional representation of the teeth segment may be reconstructed. This may allow a virtual reconstruction of the three-dimensional structure in a computerized environment or a physical reconstruction in a CAD/CAM apparatus. For example, a particular application is imaging of a segment of teeth having at least one missing tooth or a portion of a tooth. In such an instance, the image can then be used for the design and subsequent manufacture of a crown or any other prosthesis to be fitted into this teeth segment.

FIG. **2**A illustrates optics **200** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **200** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**.

The optics **200** include an illumination module **38**, a unidirectional mirror or beam splitter **40**, a series of lenses that may correspond to confocal focusing optics **42**, and folding prism **220** arranged along an optical path traversed by an array of light beams **225**. The optical path is shown to be a linear path. However, in embodiments one or more of the components of optics **200** may change a direction of the optical path. For example, the folding prism **220** may include a mirror (not shown) that may reflect light beams at an angle. An example of such a folding prism is shown in FIG. **3**B. Referring back to FIG. **2**, an imaging axis **240** is shown that is aligned to the optical path traversed by the array of light beams **225**. The imaging axis **240** is a Z-axis that represents depth. As used herein, the imaging axis (or Z axis) may be a curvilinear coordinate axis that corresponds to the optical path. Thus, if the optical path changes direction, the imaging axis changes direction correspondingly.

Illumination module **38** is a source of multiple light beams. In one embodiment, illumination module is a micro lens array that divides an incoming light beam into array of light beams **225**. In one embodiment, the array of light beams output by the illumination module **38** is an array of telecentric light beams. Accordingly, chief rays of the array of light beams may be parallel to each other. Unidirectional mirror or beam splitter **40** is disposed along the optical path of the array of light beams, and passes the array of light beams received from the unidirectional mirror or beam splitter **40**.

In one embodiment, the confocal focusing optics are divided into a series of lens groups including a first lens group **205**, a second lens group **215** and a third lens group **210**. First and/or second lens groups **205**, **215** may act as relay optics. The first and second lens groups **205**, **215** are configured to focus the array of light beams and compensate for optical aberrations. Optical aberrations that may be corrected include shape aberrations, coma, stigmatism, and so forth. In one embodiment, the first and second lens groups **205**, **215** are configured to produce an approximately rectangular field having minimal optical distortion. The first lens group **205** and second lens group **215** may have a fixed position relative to each other and to other components of the optics **200**. The third lens group **210** has a variable location that may be adjusted to change a location of a curved focal surface produced by the optics **200**.

The third lens group **210** is movable along the imaging axis (z axis), but has a fixed position normal to the imaging axis. A focusing setting of the focusing optics can be adjusted by moving the third lens group **210** along the imaging axis. Third lens group **210** may be adjusted to perform scanning of an object. To scan an object, the third lens group **210** may be displaced to numerous different locations (encoder positions) along the imaging axis **240**, and images may be taken at each location. In one embodiment, an axial gain of the focusing optics is approximately 7×. Accordingly, a displacement of the third lens group **210** adjusts a location of a curved focal surface **230** by seven times the amount of displacement. For example, a 1 mm displacement of the third lens group **210** causes a position of the curved focal surface (also referred to as a curved focal plane) by 7 mm. This enables the optics **200** to be compact and minimizes movement during operation.

In one embodiment, second lens group **215** focuses the array of light beams **225** into prism **220**, which may be a folding prism. Prism **220** may be configured to provide an appropriate refractive index (e.g., that corresponds to a refractive index of glass).

The optics **200** lack any field lens. A field lens is used to flatten a focal surface (flatten an imaging field) to achieve a flat focal plane. As shown, there is no field lens between the illumination module **38** and the unidirectional mirror or beam splitter **40**. Nor is there a field lens near prism **220** or a field lens between the unidirectional mirror or beam splitter **40** and a detector (not shown). The lack of a field lens introduces numerous advantages over confocal imaging apparatuses that use field lenses. The field lens is a diverging lens that causes a radius of the lenses used for the focusing optics and/or for relay optics to be larger. This in turn increases the amount of material (e.g., glass) used in the lenses and thus increases a weight of the confocal imaging apparatus. Additionally, the larger lenses cause a thickness of the confocal imaging apparatus to be larger. For example, an example confocal imaging apparatus with a field lens includes a largest lens having a distance from an optical axis to an outer perimeter of the lens of about 15 mm. In contrast, the same confocal imaging apparatus without a field lens may include a largest lens having a distance from the optical axis to an outer perimeter of the lens of less than 15 mm (e.g., less than 13 mm or about 9 mm in embodiments).

In a confocal imaging apparatus having a field lens, the field lens may be positioned between the illumination module **38** and the unidirectional mirror or beam splitter **40**. This causes a spacing between the illumination module **38** and the unidirectional mirror or beam splitter **40** to be about 7 mm. Additionally, a corresponding field lens would be placed between the unidirectional mirror or beam splitter **40** and a detector (not shown) at a distance of about 7 mm. In contrast, by eliminating the field lens, the distance **235** between the illumination module **38** and the unidirectional mirror or beam splitter **40** may be less than 7 mm (e.g., less than 5 mm or about 2 mm in embodiments). This further reduces the size of the confocal imaging apparatus.

As mentioned, if a field lens is used in a confocal imaging apparatus, then in actuality two field lenses are used. These two field lenses should be matching field lenses and should be carefully aligned to one another. This alignment can be a time consuming process. Additionally, failure to exactly align these field lenses introduces inaccuracy into the confocal imaging apparatus. Accordingly, an accuracy of the confocal imaging apparatus can be improved and an ease of manufacture for the confocal imaging apparatus can be improved by eliminating the field lens.

The lack of a field lens causes the focal surface **230** to be a curved focal surface (or other non-flat focal surface). The

shape of the curved focal surface **230** may depend on the focusing setting of the focusing optics (e.g., the location of the third lens group **210**). The curved focal surface may introduce significant error into the confocal imaging apparatus, which accounts for the inclusion of field lenses in prior confocal imaging apparatuses. However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the lack of a field lens.

As shown, the confocal focusing optics is a non-telecentric optical system. Accordingly, magnification of an imaged object may change with changes in depth and/or in changes of focal settings. However, such magnification changes (and any accompanying distortion) may be accommodated and corrected by the field compensator based on application of a field curvature model. Alternatively, the confocal focusing optics may operate in a telecentric mode, and distance-introduced magnification changes may be avoided.

FIG. **2**B illustrates optics **250** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **250** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200**, optics **250** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. The series of lens groups include a first lens group **255** with a fixed position and a second lens group **265** that is movable along an imaging axis **280** corresponding to a direction of propagation for an array of light beams **270**.

The array of light beams **270** are focused onto a curved focal surface **275**. Though the optics **250** are not telecentric, magnification is preserved (fixed) with changes in focusing settings because the array of light beams are collimated between first lens group **255** and second lens group **265**. For optics **250**, axial gain is 1×. Accordingly, a displacement of 1 mm of the second lens group **265** causes a displacement of the curved focal surface of 1 mm.

An object may be placed along the beam path to be imaged. The array of light beams **285** reflect off of the object and an array of returning light beams return back through the series of lens groups. The array of returning light beams **285** is then reflected by the unidirectional mirror (or beam splitter) **40** onto detector **68**. As shown, the optics **250** lack a field lens between the unidirectional mirror or beam splitter **40** and the illumination module **38** and further lack a field lens between the unidirectional mirror or beam splitter **40** and the detector **68**. Accordingly, the focal surface for the optics **250** is a curved focal surface **275**.

Embodiments have been discussed herein with reference to a confocal imaging apparatus that lacks a field lens and that has a curved focal surface. However, in some embodiments the confocal imaging apparatus includes one or more field lenses and thus has a flat focal surface. For such embodiments, the confocal imaging apparatus operates in a non-telecentric mode, and magnification at a focal plane changes with changes in focusing settings of the confocal imaging apparatus.

FIG. **2**C illustrates one example of optics **285** for a confocal imaging apparatus that includes a field lens, in accordance with one embodiment. The optics **285** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200** and optics **250**, optics **285** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. However, optics **285** also include a field lens **288** that causes a flat focal plane **299**. The series of lens groups include a first lens group **290** with a fixed position, a second lens group **292** with a fixed position and a third lens group **294** that is movable along an imaging axis **297** corresponding to a direction of propagation for an array of light beams **298**.

The array of light beams **298** are focused onto flat focal plane **299**. Magnification at the flat foal plane **299** changes with changes in focusing settings. The changes in magnification may introduce significant error into the confocal imaging apparatus. Accordingly, the focusing optics for some large field confocal imaging apparatuses maintain the same magnification with changes in focusing settings (e.g., with changes in a position of one or more lenses along an imaging axis). However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the change in magnification.

FIGS. **3**A-**3**B illustrate a probing member **300** in accordance with one embodiment. The probing member **300** is made of a light transmissive material such as glass. In one embodiment, the probing member **300** acts as a prism and corresponds to prism **220** of FIG. **2**. Probing member **300** may include an anterior segment **301** and a posterior segment **302**, tightly bonded (e.g., glued) in an optically transmissive manner at **303**. Probing member **300** may additionally include a slanted face **304** covered by a reflective mirror layer **305**. A window **306** defining a sensing surface **307** may be disposed at a bottom end of the anterior segment **301** in a manner leaving an air gap **308**. The window **306** may be fixed in position by a holding structure which is not shown. An array of light rays or beams **309** are represented schematically. As can be seen, the array of light beams **309** are reflected at the walls of the probing member at an angle in which the walls are totally reflective and finally reflect on mirror layer **305** out through the sensing face **307**. The array of light beams **309** focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure).

Various components of the confocal imaging apparatus may dissipate considerable amounts of heat relative to a size of the confocal imaging apparatus. For example, the confocal imaging apparatus may include a CMOS sensor and an FPGA, both of which may produce heat. Accordingly, internal temperatures of the confocal imaging apparatus may rise over time during use. At any given time, different portions of the confocal imaging apparatus may have different temperatures. A temperature distribution within the confocal imaging apparatus is referred to as a thermal state of the confocal imaging apparatus. The thermal state of the confocal imaging apparatus may affect various optical parameters. For example, the thermal state may cause the positions of one or more optical components to move within the confocal imaging apparatus due to expansion of the various components in accordance with thermal expansion coefficients of these components. Additionally, the refractive coefficient of one or more lens of the confocal imaging apparatus may change with changes in the thermal state. Such changes cause measurements produced by the confocal imaging apparatus to change with changes in the internal thermal state. Some regions of the confocal imaging apparatus are more sensitive to thermal change than others (e.g., due to a high optical gain). For example, some optical elements may have an axial gain of up to about 7.5 in an embodiment. For such optical elements, a 10 μm movement due to changes in the thermal state could cause up to a 75 μm shift in a measurement. Accordingly, in some embodiments, as shown in FIGS. **3**C-**3**D, an internal target is used to adjust for measurement changes caused by changes in the thermal

state. Alternatively, multiple temperature sensors may be disposed within the confocal imaging apparatus and used to determine changes in the thermal state.

FIGS. **3C-3D** illustrate a probing member **370** that includes an internal target **380**, in accordance with one embodiment. The probing member **370** is substantially similar to probing member **300**. For example, probing member **370** may be made of a light transmissive material such as glass, and may act as a prism. Probing member **370** may include an anterior segment **371** and a posterior segment **372**, tightly bonded (e.g., glued) in an optically transmissive manner. Probing member **370** may additionally include a slanted face covered by a reflective mirror layer. A window **376** defining a sensing surface may be disposed at a bottom end of the anterior segment **371**. The window **376** may be glass or another transparent material, and may be fixed in position by a holding structure which is not shown.

Probing member **370** additionally includes internal target **380** secured to the anterior segment **371** of the probing member **370** within a field of view (FOV) of the probing member **370**. The internal target **380** may be a rigid reflective material that will reflect light beams. The internal target **380** may be secured at a fixed position within the probing member **300**. Since the internal target **380** is a part of the probing member **370**, the location of the internal target **380** should remain constant. In one embodiment, the internal target **380** takes up approximately 500 μm to 1 mm of the FOV.

During measurement, an array of light rays or beams **390-392** is projected out of the anterior segment **371**. As can be seen, the internal target **380** is in the path of light beams **390**. Accordingly, the light beams **390** are reflected off of the internal target **380**, which provides a depth (z-axis) measurement of the internal target **380**. Since the internal target **380** is at a fixed position, the measured depth of the internal target **380** should not change. Accordingly, any measured change in the position of the internal target **380** reflects changes in internal optics associated with the thermal state of the confocal imaging apparatus.

The light beams **392** project through the window **376** and focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure). Alternatively, the internal target **380** may be included in an imaging apparatus with a flat focal surface (e.g., an imaging apparatus with a field lens). Such an imaging apparatus may or may not be a confocal imaging apparatus. These light beams **392** may be used to measure the position of an object in the FOV of the confocal imaging apparatus. The measured change in the position of the internal target **380** can be used to correct for measurement errors caused by the thermal state. Any apparent change in the z-axis position of the internal target **380** may be used to apply an adjustment factor to other z-axis measurements of the imaged object to compensate for changes in the focusing optics caused by temperature. Additionally, a change in the z-axis position of the internal target may be used to apply an adjustment to the X and Y pixel measurements in embodiments. In one embodiment, the z-axis position of the internal target and measured points of an object are input into a thermal state compensation model to compensate for the thermal state. In one embodiment, the thermal state compensation model is a three dimensional polynomial function.

FIG. **4** is a schematic illustration of a confocal imaging apparatus **450**, in accordance with one embodiment. In one embodiment, the confocal imaging apparatus **450** corresponds to confocal imaging apparatus **20** of FIG. **1**A. In one embodiment, components of confocal imaging apparatus **20** correspond to like named components illustrated in optics **200** of FIG. **2**. In confocal imaging apparatus **450** a parent light beam **452** may be a combination of light emitted by multiple lasers **454**A, **454**B and **454**C. Alternatively, the parent light beam **452** may be produced by a single laser (e.g., **454**B). An illumination module **456** (e.g., an optic expander) then expands the single parent beam into an array of incident light beams **458**. Incident light beams pass through a unidirectional (e.g., unidirectional) mirror or beam splitter **460**, then through focusing optics **462** towards an object **464** to be imaged.

Parent beam **452** may include multiple different wavelengths, with a different wavelength being transmitted from each laser **454**A-C. Thus, parent light beam **452** and one or more incident light beams in the array of light beams **458** may be composed of multiple different light components. Alternatively, each light beam in the array of light beams may include a single wavelength from the multiple wavelengths of parent beam **452**. Lasers **454**A-C may be arranged such that each light beam focuses on a different curved focal surface, P_A, P_B and P_C, respectively. In the position shown in FIG. **4**, incident light beam **458**A reflects off of the surface at spot **470**A, which in the specific optical arrangement of optics **462** is in the focal point for light component A (emitted by laser **454**A). Thus, a returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel. In one embodiment, the detector is a two-dimensional array of spectrophotometers, e.g. a 3 CHIP CCD sensor. Similarly, different maximal intensity will be reached for spots **470**B and **470**C for light components B and C, respectively. Thus, by using different light components each one focused simultaneously at a different plane, the time used to complete a measurement can be reduced as different focal plane ranges can simultaneously be measured.

In an alternative embodiment, only a single wavelength of light is emitted (e.g., by a single laser). Thus, parent beam **452** and the array of light beams **458** may include a single wavelength. In such an embodiment, each of the light beams in the array of light beams **458** focuses on the same curved focal surface P_C. Thus in the position shown in FIG. **4**, incident light beam **458**A reflects off of the surface at spot **470**A which in the specific focusing setting of focusing optics **462** is at the focal point for focusing optics **462**. Thus, the returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel and is registered as the z-axis position for spot **470**C. Similarly, incident light beams **458**A, **458**B reflect off of the surface at spots **470**A and **470**B, respectively. However, the spots **470**A, **470**B are not on the curved focal surface P_C. Accordingly, light is reflected back in a blurred manner from the object **464** for those spots. By changing the focusing setting for focusing optics **462** so that the focal point aligns with spot **470**B and separately with **470**A, corresponding depths associated with those focusing settings may be detected for spots **470**B and **470**A, respectively.

FIG. **5**A is a flow chart showing one embodiment of a method **500** for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface. Method **500** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **500** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment,

at least some operations of method **500** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described in embodiments herein has a non-flat (e.g., curved) focal surface. This curved focal surface introduces inaccuracies in depth measurements of points of a scanned object. For example, a first point of the object at a center of the confocal imaging apparatus' imaging field may be in focus and thus cause a highest intensity measurement at a depth Z_i. However, a second point of the object at an edge of the imaging field that has a same depth as the first point may be in focus and cause a highest intensity measurement at a depth Z_i+X due to the non-flat focal surface, where X represents the difference between the focal point at the center of the imaging field and the focal point at the edge of the imaging field. Thus, the non-flat imaging field will cause measurements of the first and second points to yield different depth values even though they are at the same depth. In one embodiment, calibration method **500** is performed to calibrate the confocal imaging apparatus so that the error introduced by the non-flat focal surface can be eliminated.

At block **505** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the final accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a final desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns.

Various calibration objects may be used, a few examples of which are set forth herein. One example calibration object is a sphere with a very accurate radius on an accurate X-Y-Z stage. Another example calibration object is a flat plate with a grid of horizontal and vertical lines printed on a surface of the plate. A flatness of the plate and the line spacing may be very accurate. Another example calibration object is a flat plate with circles or dots printed on a surface of the plate. The flatness of the plate and the size and spacing of the circles may be very accurate. Many other calibration objects may also be used. FIG. **5**C illustrates one example calibration object **590**, which is a flat plate with a grid of precisely spaced circles or dots.

Referring back to FIG. **5**A, the calibration object is measured at each focusing setting (e.g., encoder position) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object.

In one embodiment, the calibration object is mounted to a calibration jig, which may precisely move the calibration object in one or more dimensions. For example, the calibration object **590** may be mounted to the calibration jig, and the calibration jig may be moved along the z-axis. In one embodiment, the calibration jig moves the calibration object in 1 mm increments, with an accuracy of 1 μm. The calibration jig may move the calibration object in such a way as to cover more than the full field of view of the confocal imaging apparatus (e.g., the calibration object may be larger than the FOV of the confocal imaging apparatus) and to cover more than the range for the depth of scanning of the confocal imaging apparatus.

In the example of the calibration object **590**, the calibration object **590** may be scanned in two ways. A first scan may be performed at each depth position of the calibration object **590** using regular confocal scanning. This will provide a z-position for each dot in the coordinate system of the confocal imaging apparatus (e.g., based on the coordinates of the encoder that positions the lens). A second scan may be performed to generate an image of the dots at focus for each focal setting. The image may be used to determine an X, Y position for the center of each dot in pixel coordinates and with sub-pixel accuracy.

At block **510**, the measurements of the calibration object (measurements of the calibration object's surface topology) are compared to a known surface topology of the calibration object. Each point in the calibration object (e.g., each dot in calibration object **590** having a measured x-pixel, y-pixel and encoder value) may be paired to a corresponding real world point (point in a world coordinate system) from the calibration object, where the world coordinate system corresponds to known X, Y, Z coordinates of the calibration object. For example, the X and Y coordinates for calibration object **590** would correspond to known fixed positions of the dots, and the Z coordinate for calibration object **590** would depend on a setting of a calibration jig. For each point of the calibration object, a difference between a measured depth value and a known depth value may be determined. Additionally, for each point of the calibration object, a difference between a measured X and Y position and a known X and Y position may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **515**, the determined differences of the multiple points may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. The function is referred to herein as a un-distortion function. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature(object)}(x,y,Z_{optics})=a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \tag{1}$$

Where x and y are the X, Y coordinates for points on a plane normal to the imaging axis. Alternatively, a higher order polynomial may be used. The smooth function with the solved constants may then be used as an accurate field curvature model. Every parameter may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. This may result in an 18 parameter field curvature model if the above described bivariate quadratic polynomial is used.

Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape). In such an embodiment, a generated model may have a different number of parameters (e.g., 12 parameters if a function describing a conic shape is used). Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS) method) may be applied to find the best values for the constants. As mentioned, this process may be performed for each focusing setting. This is because the amount of field curvature may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate field

curvature model may be generated for each focusing setting. Alternatively, a single field curvature model may be generated that accounts for the changes to the field curvature model due to changes in the focusing setting.

In embodiments, X and Y positions are solved for at the same time that the depth is solved for. For example, differences in X and Y position at different focus settings may also be applied to solve for the constants in the smooth function. Additionally, other types of geometric correction may be solved for as well using this technique. All such geometric corrections may be solved for together. Other types of phenomena that may be corrected for using this technique include magnification change, optical distortion (e.g., non-constant magnification in x and y), optical aberrations, and so on. All such distortions may be solved for together.

FIG. **5**D illustrates a chart **594** showing a distribution of points of the calibration object **590** as measured by the confocal imaging apparatus (in the coordinate system of the confocal imaging apparatus). Chart **594** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots appear to lie on a curved surface. FIG. **5**E illustrates a chart **597** showing a distribution of points in the real world. Chart **597** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots lie on a plane. After calibration, the transformation for each dot may be determined to correct for optical distortions. Thus, the true world position of each dot may be accurately measured.

At block **525**, a temperature dependence of the confocal imaging apparatus (e.g., the focusing optics and of a lens housing for the focusing optics) is determined. In one embodiment, the operations of one or more of blocks **505-515** are performed at multiple temperatures over a temperature operating range of the confocal imaging apparatus to determine the temperature dependence. Changes in temperature may cause differences in the measured depth values. Accordingly, a temperature dependency may be determined and applied to the field curvature model to create a thermal state correction model. For example, the field curvature model may be modified from x, y, z=F(i, j, encoder) to x, y, z=F(i, j, encoder, T_{state}), where x, y and z represent real world coordinates, i represents an x-pixel, j represents a y-pixel, encoder represents a focal setting (encoder position), and T_{state} represents a thermal state. For such a model that takes into account the thermal state, an estimate of the thermal state should be obtained for each measurement. A thermal state correction model may also be generated for an imaging apparatus with a flat focal surface using the same process as described herein for an imaging apparatus with a curved focal surface.

In one embodiment, opto-mechanical simulation is performed to determine a relationship between temperature and adjustments in calibration of the focusing optics. This relationship may be used to determine a correction that may be applied to all parameters of the generated field curvature model or models, where the amount of correction is based on a current temperature.

In one embodiment, the main change in the focusing optics due to temperature is a focus shift. Curvature of the non-flat focal surface may be practically unchanged by changes in temperature. In one embodiment, a shift in focus for focusing settings may be determined by scanning one or more elements (e.g., an internal target such as internal target **380** of FIGS. **3**C-**3**D) of the confocal imaging apparatus that is near or along the optical path. In one embodiment, the scanned element is on a side of a field of view (FOV) of the confocal imaging apparatus. This element may be kept at the same distance relative to one or more components of the focusing optics. With each scan, when the 3D surface of an object is captured, the edge of the FOV where the internal target is located captures a position of the internal target. Due to the fact that the internal target is part of the confocal imaging apparatus and has a fixed position, detected changes in the position of the internal target are caused by changes in the thermal state. Accordingly, if a focus shift of the internal target is detected from the scan, then an adjustment factor may be applied to the field curvature model to compensate for the thermal state.

In one embodiment, separate field curvature models are generated for each temperature value or range of the confocal imaging apparatus at a particular focusing setting. Alternatively, a single model may be generated for each focusing setting that accounts for changes in temperature. Alternatively, a temperature dependent adjustment factor may be determined and applied to the field curvature model or models based on a measured temperature.

In one embodiment, a simple model may be used that assumes that optical change caused by the thermal state is primarily due to a linear shift in the focal setting (e.g., a backward motion in the encoder position). For such a model, changes caused by the thermal state may be corrected by adding the difference between a current measured internal target position and a reference value to every focal setting (encoder value) before applying the un-distortion function. The simple model may have the form of:

$$x,y,z=F(i,j,\text{encoder}-(\text{internal target position}-\text{reference target position})) \quad (2)$$

where F is the un-distortion function, such as function (1) above.

In another embodiment, a more complex model is used that assumes internal target effects are caused by the focal shift of encoder, but in a complex way. Such a model may have the form of:

$$x,y,z=F(i,j,f(\text{encoder},\text{internal target position})) \quad (3)$$

In another embodiment, a model that corrects for distortions caused by the thermal state assumes that the thermal state changes all optics by a small amount that can be linearly estimated. Such a model may have the form of:

$$x,\ y,\ z = F_{hot}(i,\ j,\ \text{encoder})\frac{(p-a)}{(b-a)} + F_{cold}(i,\ j,\ \text{encoder})\left(1-\frac{(p-a)}{(b-a)}\right) \quad (4)$$

where F_{hot} is the un-distortion function under a hot condition, F_{cold} is the un-distortion function under a cold condition, a is the internal target position in the hot condition, b is the internal target position in the cold position, and p is the measured internal target position.

At block **535**, the one or more generated field curvature models for the confocal imaging apparatus are stored. The field curvature models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the field curvature models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The Field curvature model (or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface of the confocal imaging apparatus. If calibration information is stored in memory of the confocal imaging apparatus, then

the field curvature models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received field curvature models to correct for the field curvature of the confocal imaging apparatus.

FIG. **5**B is a flow chart showing one embodiment of a method **550** for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification. Method **550** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **550** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment, at least some operations of method **550** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described with reference to method **550** may have a non-flat (e.g., curved) focal surface or a flat focal plane. Moreover, the confocal imaging apparatus described with reference to method **550** has focusing optics that are configured so that changes in a focusing setting cause a change in magnification at the focal surface or focal plane. This change in magnification introduces inaccuracies in X and Y position measurements of points of a scanned object. For example, a point of the object might be measured to have a first X and Y position at a first focusing setting, but might be measured to have a second X and Y position at a second focusing setting. Thus, the magnification changes will cause measurements to yield different X, Y values as the focusing setting changes. In one embodiment, calibration method **550** is performed to calibrate the confocal imaging apparatus so that the inaccuracies introduced by the changes in magnification can be eliminated.

At block **555** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the final accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a final desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns. Any of the calibration objects described with reference to FIG. **5**A may be used.

The calibration object is measured at each focusing setting (encoder value) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object. Based on these measurements, a list of coordinates is collected in both the calibration object space (e.g., real world) and in the sensor/optics space (e.g., virtual space). In the calibration object space, each set of coordinates for a point of the object has an X_{obj}, Y_{obj} and Z_{obj} coordinate. These coordinates are known to be accurate due to the known information about the calibration object. In the sensor/optics space, each set of coordinates for a point of the object includes an X_{pix}, Y_{pix}, Z_{optics} coordinate, where X_{pix} and Y_{pix} are determined based on the pixel detecting the point and Z_{optics} is the lens position of the focusing optics (e.g., the focusing setting).

At block **560**, the measurements of the calibration object (measurements of the calibration object's surface topology) may be compared to a known surface topology of the calibration object. For each point of the calibration object, a difference between a measured depth value, X value and/or Y value and a known depth value, X value and/or Y value may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **562**, it is determined whether the focusing optics have a curved focal surface. If the focusing optics do have a curved focal surface, the method proceeds to block **565**. Otherwise the method proceeds to block **570**.

At block **565**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature(object)}(x,y,Z_{optics})=a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \quad (5)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape), such as a polynomial of higher order. The smooth function with the solved constants may then be used for an accurate field curvature model.

At block **570**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional or higher dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on an x-axis caused by changes in the focusing setting (e.g., changes in the Z_{optics} value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$X_{Object}(x,y,Z_{optics})=b_1x^2+b_2y^2+b_3x+b_4y+b_5xy+b_6 \quad (6)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the X coordinate.

At block **575**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on a y-axis caused by changes in the focusing setting (e.g., changes in the Z value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Y_{Object}(x,y,Z_{optics})=c_1x^2+c_2y^2+c_3x+c_4y+c_5xy+c_6 \quad (7)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function

(e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the Y coordinate.

Blocks **565**, **570** and **575** have been described as three separate operations. However, in some embodiments a single operation may be performed to solve for each of the x-coordinate, the y-coordinate and the z-coordinate. For example, an un-distortion function having the following form may be solved to determine the x, y and z coordinates.

$$F_X(x,y,z)=a_0+a_1x+a_2y+a_3z+a_4x^2+a_5y^2+a_6z^2+\ldots+a_ixy+\ldots+a_jx^ny^mz^k$$

$$F_Y(x,y,z)=b_0+b_1x+b_2y+b_3z+b_4x^2+b_5y^2+b_6z^2+\ldots+b_ixy+\ldots+b_jx^ny^mz^k$$

$$F_Z(x,y,z)=c_0+c_1x+c_2y+c_3z+c_4x^2+c_5y^2+c_6z^2+\ldots+c_ixy+\ldots+c_jx^ny^mz^k \quad (8)$$

where F_X, F_Y and F_Z are the functions whose results in world coordinates are to be solved for, x and y are pixel coordinates measured by the confocal imaging apparatus, z is a focal setting (e.g., encoder coordinates corresponding to a focal setting), a_i, b_i and c_i are learned parameters, and n, m and k are the maximal degree of the nominal. The function may be selected to minimize a mean square error between the world coordinates and the found positions after the function transformation. Outlier positions may be detected and removed before fitting. In one embodiment, a number of non-zero parameters is constrained.

At block **580**, one or more optics correcting models are generated based on the first second and third polynomial functions (or other smooth functions), such as those represented in equations 5-8. Every parameter for equations 5-8 may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. In one embodiment, each parameter is modeled as a quadratic change to the Z_{optics} (focusing setting). For example, parameter a_1 may be a parameter having a form:

$$a_1(Z_{Optics})=A+B*Z_{Optics}+C*Z_{Optics}^2 \quad (9)$$

Parameters a_2-a_6, b_1-b_6 and c_1-c_6 may be similarly represented. This may result in a 54 parameter model that corrects for full curvature, magnification and distortion of the field of view (FOV).

Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS) method) may be applied to find the best values for the constants at each of blocks **565**, **570** and **575**. As mentioned, these processes may be performed for each focusing setting. This is because the amount of field curvature and magnification may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate model may be generated for each focusing setting. Alternatively, a single model may be generated that accounts for the changes to the model due to changes in the focusing setting. Note that temperature dependence may also be determined and included in the model as described with reference to block **525** of method **500**. In one embodiment, a temperature dependence is determined, and a model that corrects for thermal state is created, as discussed above with reference to method **500**.

At block **585**, the one or more generated models for the confocal imaging apparatus are stored. The models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the

models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The model (or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface as well as to correct for inaccuracies caused by changes in magnification. If calibration information is stored in memory of the confocal imaging apparatus, then the models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received models to correct for the field curvature and/or magnification changes of the confocal imaging apparatus.

FIG. **6** is a flow chart showing one embodiment of a method **600** for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model or other model (e.g., a thermal state compensation model) calibrated to a confocal imaging apparatus or other imaging apparatus (e.g., a stereoscopic imaging apparatus). Method **600** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **600** are performed by a computing device (e.g., computing device **24** of FIG. **1**B executing image processing module **82**).

At block **605** of method **600**, processing logic receives intensity measurements generated by pixels of a detector of a confocal imaging apparatus. The detector may have a two-dimensional array of pixels, and each pixel may receive a particular light beam of an array of light beams directed at the detector. The array of light beams may be an array of returning light beams that have been reflected off of a surface of the imaged three dimensional object. Thus, each pixel of the detector is associated with a particular point of the three dimensional object and provides intensity measurements for an associated returning light beam from the array of returning light beams.

Each received intensity measurement is associated with a particular focusing setting of the confocal imaging apparatus. Intensity measurements may be received over a range of focusing settings. At block **620**, processing logic determines, for each pixel, a focusing setting of the confocal imaging apparatus that provides a maximum measured intensity.

A relative distance between a probe of the confocal imaging apparatus and a focal point of the confocal imaging apparatus may be known for each focusing setting (encoder value). A point of the imaged object is known to be in focus (e.g., at the focal point) when a measured intensity for that point is maximal. Accordingly, at block **630** processing logic determines, for each pixel, a depth of a point of the three dimensional object associated with that pixel that corresponds to the focusing setting that yielded the maximal intensity. If the imaging apparatus includes an internal target in the FOV of the imaging apparatus, then some pixels will be associated with points on the internal target. Accordingly, a depth of the points of the internal target may also be determined.

As discussed previously herein, the non-flat focal surface and/or magnification changes of the confocal imaging apparatus introduce an error in the depth measurements and/or in the X, Y coordinate measurements. Accordingly, at block **640** processing logic adjusts the determined depths of points of the imaged three dimensional object based on applying the determined focusing settings for the pixels associated with those points to a field curvature model. Processing logic

may additionally or alternatively determine X, Y coordinates of the points based on applying the determined focusing settings to the field curvature model or other model. One or more field curvature models and/or other models may be used. For example, a particular field curvature model and/or other model may be associated with each focusing setting. An appropriate field curvature model may be identified based on the focusing setting at which a point on the object came into focus. A particular depth adjustment for that point may then be determined by providing the X, Y coordinates of the pixel into the determined field curvature model. Alternatively, a single field curvature model may be used, and the X, Y coordinates and focusing setting may be input into the field curvature model to determine the depth displacement. In one embodiment, a temperature of the focusing optics is also measured and/or a thermal state is otherwise determined (e.g., using an internal target position), and an additional depth adjustment factor (and/or other optical adjustment) is determined based on the temperature (e.g., using a thermal state compensation model). This additional depth adjustment factor (and/or additional optical adjustment) may then be applied to the measured depths (and/or X and Y coordinates) of all points. In one embodiment, a single model is used that compensates for both the thermal state and field curvature.

At block **650**, processing logic may determine a shape (e.g., surface topology) of the three dimensional object based on the adjusted depths and/or x and y coordinates. Processing logic may then create an accurate virtual three dimensional model of the imaged object.

FIG. **7** illustrates a diagrammatic representation of a machine in the example form of a computing device **700** within which a set of instructions, for causing the machine to perform any one or more of the methodologies discussed herein, may be executed. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet computer, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein. In one embodiment, computing device **700** corresponds to computing device **24** of FIG. **1**B.

The example computing device **700** includes a processing device **702**, a main memory **704** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM), etc.), a static memory **706** (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory (e.g., a data storage device **728**), which communicate with each other via a bus **708**.

Processing device **702** represents one or more general-purpose processors such as a microprocessor, central processing unit, or the like. More particularly, the processing device **702** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processing device **702** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. Processing device **702** is configured to execute the processing logic (instructions **726**) for performing operations and steps discussed herein.

The computing device **700** may further include a network interface device **722** for communicating with a network **764** or other device. The computing device **700** also may include a video display unit **710** (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), an alphanumeric input device **712** (e.g., a keyboard), a cursor control device **714** (e.g., a mouse), and a signal generation device **720** (e.g., a speaker).

The data storage device **728** may include a machine-readable storage medium (or more specifically a non-transitory computer-readable storage medium) **724** on which is stored one or more sets of instructions **726** embodying any one or more of the methodologies or functions described herein. A non-transitory storage medium refers to a storage medium other than a carrier wave. The instructions **726** may also reside, completely or at least partially, within the main memory **704** and/or within the processing device **702** during execution thereof by the computer device **700**, the main memory **704** and the processing device **702** also constituting computer-readable storage media.

The computer-readable storage medium **724** may also be used to store a field compensator **750** which may correspond to field compensator **92** of FIG. **1**B. The computer readable storage medium **724** may also store a software library containing methods that call the field compensator **750**. While the computer-readable storage medium **724** is shown in an example embodiment to be a single medium, the term "computer-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "computer-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present invention. The term "computer-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent upon reading and understanding the above description. Although embodiments of the present invention have been described with reference to specific example embodiments, it will be recognized that the invention is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A confocal imaging apparatus comprising:

an illumination module to generate an array of light beams;

focusing optics comprising a plurality of lenses disposed along an optical path of the array of light beams, the focusing optics to perform confocal focusing of the array of light beams onto a non-flat focal surface and to direct the array of light beams toward a three dimensional object to be imaged;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the non-flat focal surface along an imaging axis defined by the optical path; and

a detector to measure intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the array of returning light beams are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface.

2. The confocal imaging apparatus of claim **1**, wherein the non-flat focal surface comprises a curved focal plane and the detected positions for the one or more of the plurality of points are to be adjusted to compensate for a curvature of the curved focal plane.

3. The confocal imaging apparatus of claim **1**, further comprising:

a beam splitter disposed along the optical path between the illumination module and the focusing optics, wherein the beam splitter directs the array of light beams from the illumination module towards the focusing optics and directs the array of returning light beams from the focusing optics to the detector;

wherein the confocal imaging apparatus is characterized in having an absence of a field lens between the beam splitter and the illumination module.

4. The confocal imaging apparatus of claim **3**, wherein the confocal imaging apparatus is further characterized in having an absence of a field lens between the beam splitter and the detector.

5. The confocal imaging apparatus of claim **1**, further comprising:

a folding prism along the optical path of the array of light beams after the focusing optics, wherein the folding prism is to direct the array of light beams onto the three dimensional object to be imaged;

wherein the plurality of lenses comprise:

a first lens group disposed proximate to the illumination module;

a second lens group disposed proximate to the folding prism, the second lens group having a fixed location relative to the first lens group; and

a third lens group disposed between the first lens group and the second lens group, the third lens group having a variable location that is adjustable by the translation mechanism.

6. The confocal imaging apparatus of claim **3**, wherein the beam splitter is separated from the illumination module by a distance of less than 5 millimeters.

7. The confocal imaging apparatus of claim **1**, wherein a radius of a largest lens of the plurality of lenses is less than 13 millimeters.

8. The confocal imaging apparatus of claim **1**, further comprising a processor to:

determine, for each returning light beam of the array of returning light beams, a location of the at least one lens that yields a maximum measured intensity;

determine, for each returning light beam of the array of returning light beams, a position on the imaging axis of a point of the three dimensional object illuminated by the returning light beam that corresponds to the determined location of the at least one lens; and

adjust the position on the imaging axis of at least one point of the three dimensional object based on applying the determined location of the at least one lens to a field curvature model that is calibrated to the confocal imaging apparatus to compensate for the non-flat focal surface.

9. The confocal imaging apparatus of claim **8**, wherein the field curvature model comprises a three dimensional polynomial function.

10. The confocal imaging apparatus of claim **8**, wherein a shape of the non-flat focal surface changes with changes in the location of the at least one lens.

11. The confocal imaging apparatus of claim **8**, further comprising:

one or more elements near or along the optical path, the one or more elements having a fixed distance from at least one lens of the plurality of lenses, wherein the fixed distance changes with changes in temperature, wherein the processor is further to:

determine a current distance between the one or more elements and the at least one lens; and

apply an adjustment factor to the field curvature model based on the current distance.

12. The confocal imaging apparatus of claim **8**, wherein the array of light beams generated by the illumination module is an array of telecentric light beams.

* * * * *

EXHIBIT 2

US010507088B2

(12) **United States Patent**
Verker et al.

(10) **Patent No.: US 10,507,088 B2**
(45) **Date of Patent: *Dec. 17, 2019**

(54) **IMAGING APPARATUS WITH SIMPLIFIED OPTICAL DESIGN**

(71) Applicant: **Align Technology, Inc.**, San Jose, CA (US)

(72) Inventors: **Tal Verker**, Ofra (IL); **Adi Levin**, Nes Tziona (IL); **Ofer Saphier**, Rechovot (IL); **Maayan Moshe**, Ra'anana (IL)

(73) Assignee: **Align Technology, Inc.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **16/286,437**

(22) Filed: **Feb. 26, 2019**

(65) **Prior Publication Data**

US 2019/0192263 A1 Jun. 27, 2019

Related U.S. Application Data

(60) Continuation of application No. 15/610,515, filed on May 31, 2017, now Pat. No. 10,327,872, which is a (Continued)

(51) **Int. Cl.**
G02B 23/24 (2006.01)
G02B 21/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC .... ***A61C 9/0066*** (2013.01); ***G01B 11/24*** (2013.01); ***G02B 21/006*** (2013.01); (Continued)

(58) **Field of Classification Search**
CPC A61C 9/0066; G01B 11/24; G02B 21/006; G02B 23/2446; G02B 23/2461; G02B 23/26; G02B 27/0025
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,171,695 A 9/1939 Harper
2,467,432 A 4/1949 Kesling
(Continued)

FOREIGN PATENT DOCUMENTS

AU 3031677 A 5/1979
AU 3031677 B 7/1981
(Continued)

OTHER PUBLICATIONS

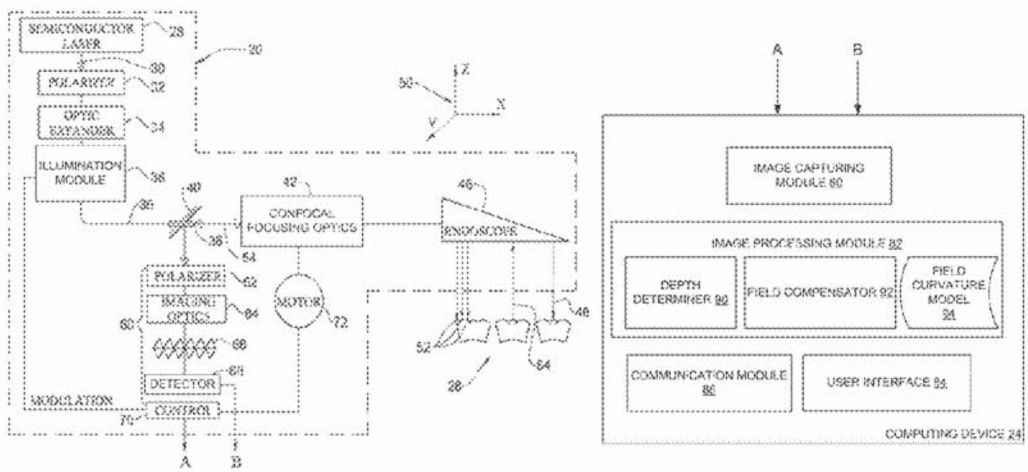
Kleeman et al., "The Speed Positioner", J. Clin. Orthod.; 30(12); pp. 673-680; Dec. 1996.
(Continued)

Primary Examiner — Isiaka O Akanbi
(74) *Attorney, Agent, or Firm* — Lowenstein Sandler LLP

(57) **ABSTRACT**

Embodiments are directed to an imaging apparatus, which in an embodiment includes a light source to provide light, optics, a translation mechanism and a detector. The optics include focusing optics to perform focusing of the light onto a non-flat focal surface and to direct the light toward a three dimensional object. The translation mechanism adjusts a location of at least one lens of the focusing optics to displace the non-flat focal surface. The detector measures intensities of returning light that is reflected off of the three dimensional object, wherein the intensities of the returning light are measured for a plurality of locations of the at least one lens for determination of positions of a plurality of points of the three dimensional object. Detected positions of one or more of the plurality of points are adjusted to compensate for the non-flat focal surface.

30 Claims, 13 Drawing Sheets



Related U.S. Application Data

division of application No. 14/825,173, filed on Aug. 13, 2015, now Pat. No. 9,675,430.

(60) Provisional application No. 62/037,778, filed on Aug. 15, 2014.

(51) **Int. Cl.**
A61C 9/00 (2006.01)
G01B 11/24 (2006.01)
G02B 27/00 (2006.01)
G02B 23/26 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 23/2446*** (2013.01); ***G02B 23/2461*** (2013.01); ***G02B 23/26*** (2013.01); ***G02B 27/0025*** (2013.01)

(58) **Field of Classification Search**
USPC 356/601, 445, 603
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,531,222 A 11/1950 Kesling
3,379,193 A 4/1968 Monsghan
3,385,291 A 5/1968 Martin
3,407,500 A 10/1968 Kesling
3,478,742 A 11/1969 Bohlmann
3,496,936 A 2/1970 Gores
3,533,163 A 10/1970 Kirschenbaum
3,556,093 A 1/1971 Quick
3,600,808 A 8/1971 Reeve
3,660,900 A 5/1972 Andrews
3,683,502 A 8/1972 Wallshein
3,738,005 A 6/1973 Cohen et al.
3,860,803 A 1/1975 Levine
3,885,310 A 5/1975 Northcutt
3,916,526 A 11/1975 Schudy
3,922,786 A 12/1975 Lavin
3,950,851 A 4/1976 Bergersen
3,983,628 A 10/1976 Acevedo
4,014,096 A 3/1977 Dellinger
4,195,046 A 3/1980 Kesling
4,253,828 A 3/1981 Coles et al.
4,255,138 A 3/1981 Frohn
4,324,546 A 4/1982 Heitlinger et al.
4,324,547 A 4/1982 Arcan et al.
4,348,177 A 9/1982 Kurz
4,419,992 A 12/1983 Chorbajian
4,433,956 A 2/1984 Witzig
4,478,580 A 10/1984 Barrut
4,500,294 A 2/1985 Lewis
4,505,673 A 3/1985 Yoshii
4,519,386 A 5/1985 Sullivan
4,526,540 A 7/1985 Dellinger
4,575,330 A 3/1986 Hull
4,575,805 A 3/1986 Moermann et al.
4,591,341 A 5/1986 Andrews
4,609,349 A 9/1986 Cain
4,611,288 A 9/1986 Duret et al.
4,656,860 A 4/1987 Orthuber et al.
4,663,720 A 5/1987 Duret et al.
4,664,626 A 5/1987 Kesling
4,676,747 A 6/1987 Kesling
4,755,139 A 7/1988 Abbatte et al.
4,757,824 A 7/1988 Chaumet
4,763,791 A 8/1988 Halverson et al.
4,764,111 A 8/1988 Knierim
4,793,803 A 12/1988 Martz
4,798,534 A 1/1989 Breads
4,836,778 A 6/1989 Baumrind et al.
4,837,732 A 6/1989 Brandestini et al.
4,850,864 A 7/1989 Diamond
4,850,865 A 7/1989 Napolitano
4,856,991 A 8/1989 Breads et al.
4,877,398 A 10/1989 Kesling
4,880,380 A 10/1989 Martz
4,886,451 A 12/1989 Cetlin
4,889,238 A 12/1989 Batchelor
4,890,608 A 1/1990 Steer
4,935,635 A 6/1990 O'Harra
4,936,862 A 6/1990 Walker et al.
4,937,928 A 7/1990 van der Zel
4,941,826 A 7/1990 Loran et al.
4,952,928 A 8/1990 Carroll et al.
4,964,770 A 10/1990 Steinbichler et al.
4,975,052 A 12/1990 Spencer et al.
4,983,334 A 1/1991 Adell
4,997,369 A 3/1991 Shafir
5,002,485 A 3/1991 Aagesen
5,011,405 A 4/1991 Lemchen
5,017,133 A 5/1991 Miura
5,027,281 A 6/1991 Rekow et al.
5,035,613 A 6/1991 Breads et al.
5,037,295 A 8/1991 Bergersen
5,055,039 A 10/1991 Abbatte et al.
5,100,316 A 3/1992 Wildman
5,103,838 A 4/1992 Yousif
5,121,333 A 6/1992 Riley et al.
5,123,425 A 6/1992 Shannon, Jr. et al.
5,128,870 A 7/1992 Erdman et al.
5,130,064 A 7/1992 Smalley et al.
5,131,843 A 7/1992 Hilgers et al.
5,131,844 A 7/1992 Marinaccio et al.
5,139,419 A 8/1992 Andreiko et al.
5,145,364 A 9/1992 Martz et al.
5,176,517 A 1/1993 Truax
5,204,670 A 4/1993 Stinton
5,242,304 A 4/1993 Truax et al.
5,245,592 A 9/1993 Kuemmel et al.
5,273,429 A 12/1993 Rekow et al.
5,278,756 A 1/1994 Lemchen et al.
5,306,144 A 4/1994 Hibst et al.
5,328,362 A 7/1994 Watson et al.
5,335,657 A 8/1994 Terry, Jr. et al.
5,338,198 A 8/1994 Wu et al.
5,340,309 A 8/1994 Robertson
5,342,202 A 8/1994 Deshayes
5,368,478 A 11/1994 Andreiko et al.
5,372,502 A 12/1994 Massen et al.
5,382,164 A 1/1995 Stern
5,395,238 A 3/1995 Andreiko et al.
5,431,562 A 7/1995 Andreiko et al.
5,440,326 A 8/1995 Quinn
5,440,496 A 8/1995 Andersson et al.
5,447,432 A 9/1995 Andreiko et al.
5,452,219 A 9/1995 Dehoff et al.
5,454,717 A 9/1995 Andreiko et al.
5,456,600 A 10/1995 Andreiko et al.
5,474,448 A 12/1995 Andreiko et al.
RE35,169 E 3/1996 Lemchen et al.
5,499,633 A 3/1996 Fenton
5,528,735 A 6/1996 Strasnick et al.
5,533,895 A 7/1996 Andreiko et al.
5,542,842 A 8/1996 Andreiko et al.
5,543,780 A 8/1996 McAuley et al.
5,549,476 A 8/1996 Stern
5,562,448 A 10/1996 Mushabac
5,570,182 A 10/1996 Nathel et al.
5,587,912 A 12/1996 Andersson et al.
5,605,459 A 2/1997 Kuroda et al.
5,607,305 A 3/1997 Andersson et al.
5,614,075 A 3/1997 Andre, Sr.
5,621,648 A 4/1997 Crump
5,626,537 A 5/1997 Danyo et al.
5,645,420 A 7/1997 Bergersen
5,645,421 A 7/1997 Slootsky
5,651,671 A 7/1997 Seay et al.
5,655,653 A 8/1997 Chester
5,659,420 A 8/1997 Wakai et al.
5,683,243 A 11/1997 Andreiko et al.
5,683,244 A 11/1997 Truax
5,691,539 A 11/1997 Pfeiffer

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,692,894 A	12/1997	Schwartz et al.
5,725,376 A	3/1998	Poirier
5,725,378 A	3/1998	Wang
5,737,084 A	4/1998	Ishihara
5,740,267 A	4/1998	Echerer et al.
5,742,700 A	4/1998	Yoon et al.
5,769,631 A	6/1998	Williams
5,774,425 A	6/1998	Ivanov et al.
5,790,242 A	8/1998	Stern et al.
5,799,100 A	8/1998	Clarke et al.
5,800,174 A	9/1998	Andersson
5,816,800 A	10/1998	Brehm et al.
5,818,587 A	10/1998	Devaraj et al.
5,823,778 A	10/1998	Schmitt et al.
5,848,115 A	12/1998	Little et al.
5,857,853 A	1/1999	van Nifterick et al.
5,866,058 A	2/1999	Batchelder et al.
5,879,158 A	3/1999	Doyle et al.
5,880,961 A	3/1999	Crump
5,880,962 A	3/1999	Andersson et al.
5,904,479 A	5/1999	Staples
5,934,288 A	8/1999	Avila et al.
5,957,686 A	9/1999	Anthony
5,964,587 A	10/1999	Sato
5,971,754 A	10/1999	Sondhi et al.
5,975,893 A	11/1999	Chishti et al.
5,980,246 A	11/1999	Ramsay et al.
5,989,023 A	11/1999	Summer et al.
6,044,309 A	3/2000	Honda
6,049,743 A	4/2000	Baba
6,053,731 A	4/2000	Heckenberger
6,068,482 A	5/2000	Snow
6,099,303 A	8/2000	Gibbs et al.
6,099,314 A	8/2000	Kopelman et al.
6,123,544 A	9/2000	Cleary
6,152,731 A	11/2000	Jordan et al.
6,154,676 A	11/2000	Levine
6,183,248 B1	2/2001	Chishti et al.
6,186,780 B1	2/2001	Hibst et al.
6,190,165 B1	2/2001	Andreiko et al.
6,200,133 B1	3/2001	Kittelsen
6,201,880 B1	3/2001	Elbaum et al.
6,212,435 B1	4/2001	Lattner et al.
6,217,334 B1	4/2001	Hultgren
6,231,338 B1	5/2001	de Josselin de Jong et al.
6,239,705 B1	5/2001	Glen
6,243,601 B1	6/2001	Wist
6,263,234 B1	7/2001	Engelhardt et al.
6,299,438 B1	10/2001	Sahagian et al.
6,309,215 B1	10/2001	Phan et al.
6,315,553 B1	11/2001	Sachdeva et al.
6,328,745 B1	12/2001	Ascherman
6,334,073 B1	12/2001	Levine
6,350,120 B1	2/2002	Sachdeva et al.
6,364,660 B1	4/2002	Durbin et al.
6,382,975 B1	5/2002	Poirier
6,402,510 B1	6/2002	Williams
6,402,707 B1	6/2002	Ernst
6,405,729 B1	6/2002	Thornton
6,436,058 B1	8/2002	Krahner et al.
6,450,807 B1	9/2002	Chishti et al.
6,482,298 B1	11/2002	Bhatnagar
6,499,995 B1	12/2002	Schwartz
6,515,593 B1	2/2003	Stark et al.
6,516,805 B1	2/2003	Thornton
6,520,772 B2	2/2003	Williams
6,524,101 B1	2/2003	Phan et al.
6,540,707 B1	4/2003	Stark et al.
6,572,372 B1	6/2003	Phan et al.
6,573,998 B2	6/2003	Cohen-Sabban
6,594,539 B1	7/2003	Geng
6,597,934 B1	7/2003	de Jong et al.
6,602,070 B2	8/2003	Miller et al.
6,611,783 B2	8/2003	Kelly, Jr. et al.
6,613,001 B1	9/2003	Dworkin
6,616,579 B1	9/2003	Reinbold et al.
6,623,698 B2	9/2003	Kuo
6,624,752 B2	9/2003	Klitsgaard et al.
6,626,180 B1	9/2003	Kittelsen et al.
6,640,128 B2	10/2003	Vilsmeier et al.
6,697,164 B1	2/2004	Babayoff et al.
6,702,765 B2	3/2004	Robbins et al.
6,702,804 B1	3/2004	Ritter et al.
6,705,863 B2	3/2004	Phan et al.
6,830,450 B2	12/2004	Knopp et al.
6,885,464 B1	4/2005	Pfeiffer et al.
6,890,285 B2	5/2005	Rahman et al.
7,036,514 B2	5/2006	Heck
7,092,107 B2	8/2006	Babayoff et al.
7,106,233 B2	9/2006	Schroeder et al.
7,112,065 B2	9/2006	Kopelman et al.
7,121,825 B2	10/2006	Chishti et al.
7,138,640 B1	11/2006	Delgado et al.
7,142,312 B2	11/2006	Quadling et al.
7,166,063 B2	1/2007	Rahman et al.
7,184,150 B2	2/2007	Quadling et al.
7,192,273 B2	3/2007	McSurdy, Jr.
7,220,124 B2	5/2007	Taub et al.
7,286,954 B2	10/2007	Kopelman et al.
7,292,759 B2	11/2007	Boutoussov et al.
7,302,842 B2	12/2007	Biester et al.
7,338,327 B2	3/2008	Sticker et al.
D565,509 S	4/2008	Fechner et al.
7,351,116 B2	4/2008	Dold
7,357,637 B2	4/2008	Liechtung
7,450,231 B2	11/2008	Johs et al.
7,458,810 B2	12/2008	Bergersen
7,460,230 B2	12/2008	Johs et al.
7,462,076 B2	12/2008	Walter et al.
7,463,929 B2	12/2008	Simmons
7,500,851 B2	3/2009	Williams
D594,413 S	6/2009	Palka et al.
7,544,103 B2	6/2009	Walter et al.
7,553,157 B2	6/2009	Abolfathi et al.
7,561,273 B2	7/2009	Stautmeister et al.
7,577,284 B2	8/2009	Wong et al.
7,596,253 B2	9/2009	Wong et al.
7,597,594 B2	10/2009	Stadler et al.
7,609,875 B2	10/2009	Liu et al.
D603,796 S	11/2009	Sticker et al.
7,616,319 B1	11/2009	Woollam et al.
7,626,705 B2	12/2009	Altendort
7,632,216 B2	12/2009	Rahman et al.
7,633,625 B1	12/2009	Woollam et al.
7,637,262 B2	12/2009	Bailey
7,668,355 B2	2/2010	Wong et al.
7,670,179 B2	3/2010	Muller
7,695,327 B2	4/2010	Bauerle et al.
7,698,068 B2	4/2010	Babayoff
7,724,378 B2	5/2010	Babayoff
D618,619 S	6/2010	Walter
7,731,508 B2	6/2010	Borst
7,735,217 B2	6/2010	Borst
7,780,460 B2	8/2010	Walter
7,787,132 B2	8/2010	Korner et al.
7,791,810 B2	9/2010	Powell
7,796,243 B2	9/2010	Choo-Smith et al.
7,806,727 B2	10/2010	Dold et al.
7,813,787 B2	10/2010	de Josselin de Jong et al.
7,824,180 B2	11/2010	Abolfathi et al.
7,828,601 B2	11/2010	Pyczak
7,845,969 B2	12/2010	Stadler et al.
7,854,609 B2	12/2010	Chen et al.
7,862,336 B2	1/2011	Kopelman et al.
7,872,760 B2	1/2011	Ertl
7,874,836 B2	1/2011	McSurdy, Jr.
7,874,849 B2	1/2011	Sticker et al.
7,878,801 B2	2/2011	Abolfathi et al.
7,907,280 B2	3/2011	Johs et al.
7,929,151 B2	4/2011	Liang et al.
7,947,508 B2	5/2011	Tricca et al.
7,959,308 B2	6/2011	Freeman et al.
7,963,766 B2	6/2011	Cronauer
7,986,415 B2	7/2011	Thiel et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,017,891 B2	9/2011	Nevin	
8,026,916 B2	9/2011	Wen	
8,027,709 B2	9/2011	Arnone et al.	
8,054,556 B2	11/2011	Chen et al.	
8,077,949 B2	12/2011	Liang et al.	
8,083,556 B2	12/2011	Stadler et al.	
D652,799 S	1/2012	Mueller	
8,118,592 B2	2/2012	Tortorici	
8,126,025 B2	2/2012	Takeda	
8,144,954 B2	3/2012	Quadling et al.	
8,160,334 B2	4/2012	Thiel et al.	
8,201,560 B2	6/2012	Dembro	
8,215,312 B2	7/2012	Garabadian et al.	
8,240,018 B2	8/2012	Walter et al.	
8,279,450 B2	10/2012	Oota et al.	
8,292,617 B2	10/2012	Brandt et al.	
8,294,657 B2	10/2012	Kim et al.	
8,297,286 B2	10/2012	Smernoff	
8,306,608 B2	11/2012	Mandelis et al.	
8,310,683 B2	11/2012	Babayoff et al.	
8,314,764 B2	11/2012	Kim et al.	
8,332,015 B2	12/2012	Ertl	
8,354,588 B2	1/2013	Sticker et al.	
8,363,228 B2	1/2013	Babayoff	
8,366,479 B2	2/2013	Borst et al.	
8,465,280 B2	6/2013	Sachdeva et al.	
8,477,320 B2	7/2013	Stock et al.	
8,488,113 B2	7/2013	Thiel et al.	
8,520,922 B2	8/2013	Wang et al.	
8,520,925 B2	8/2013	Duret	
8,556,625 B2	10/2013	Lovely	
8,570,530 B2*	10/2013	Liang	A61B 1/00009 356/601
8,573,224 B2	11/2013	Thornton	
8,577,212 B2	11/2013	Thiel	
8,594,408 B2	11/2013	Alpern et al.	
8,650,586 B2	2/2014	Lee et al.	
8,675,706 B2	3/2014	Seurin et al.	
8,723,029 B2	5/2014	Pyczak et al.	
8,743,923 B2	6/2014	Geske et al.	
8,767,270 B2	7/2014	Curry et al.	
8,768,016 B2	7/2014	Pan et al.	
8,771,149 B2	7/2014	Rahman et al.	
8,839,476 B2	9/2014	Adachi	
8,870,566 B2	10/2014	Bergersen	
8,878,905 B2	11/2014	Fisker et al.	
8,899,976 B2	12/2014	Chen et al.	
8,936,463 B2	1/2015	Mason et al.	
8,948,482 B2	2/2015	Levin	
8,956,058 B2	2/2015	Rosch	
8,992,216 B2	3/2015	Karazivan	
9,022,792 B2	5/2015	Sticker et al.	
9,039,418 B1	5/2015	Rubbert	
9,084,535 B2	7/2015	Girkin et al.	
9,108,338 B2	8/2015	Sirovskiy et al.	
9,144,512 B2	9/2015	Wagner	
9,192,305 B2	11/2015	Levin	
9,204,952 B2	12/2015	Lampalzer	
9,242,118 B2	1/2016	Brawn	
9,261,358 B2	2/2016	Atiya et al.	
9,299,192 B2	3/2016	Kopelman	
9,336,336 B2	5/2016	Deichmann et al.	
9,408,743 B1	8/2016	Wagner	
9,433,476 B2	9/2016	Khardekar et al.	
9,439,568 B2	9/2016	Atiya et al.	
9,444,981 B2	9/2016	Bellis et al.	
9,500,635 B2	11/2016	Islam	
9,506,808 B2	11/2016	Jeon et al.	
9,513,470 B1	12/2016	Weaver	
9,545,331 B2	1/2017	Ingemarsson-Matzen	
9,584,771 B2	2/2017	Mandelis et al.	
9,675,430 B2	6/2017	Verker et al.	
9,693,839 B2	7/2017	Atiya et al.	
9,744,006 B2	8/2017	Ross	
9,936,186 B2	4/2018	Jesenko et al.	
2001/0038705 A1	11/2001	Rubbert et al.	
2002/0010568 A1	1/2002	Rubbert et al.	
2002/0015934 A1	2/2002	Rubbert et al.	
2003/0009252 A1	1/2003	Pavlovskaia et al.	
2003/0048540 A1	3/2003	Xie et al.	
2003/0139834 A1	7/2003	Nikolskiy et al.	
2003/0190575 A1	10/2003	Hilliard	
2003/0207224 A1	11/2003	Lotte	
2003/0224311 A1	12/2003	Cronauer	
2004/0009449 A1	1/2004	Mah et al.	
2004/0019262 A1	1/2004	Perelgut	
2004/0058295 A1	3/2004	Bergersen	
2004/0090638 A1	5/2004	Babayoff	
2004/0094165 A1	5/2004	Cook	
2005/0031196 A1	2/2005	Moghaddam et al.	
2005/0037312 A1	2/2005	Uchida	
2005/0048433 A1	3/2005	Hilliard	
2005/0100333 A1	5/2005	Kerschbaumer et al.	
2005/0181333 A1	8/2005	Karazivan et al.	
2005/0186524 A1	8/2005	Abolfathi et al.	
2005/0244781 A1	11/2005	Abels et al.	
2006/0001739 A1*	1/2006	Babayoff	A61B 1/00009 348/49
2006/0084024 A1	4/2006	Farrell	
2006/0099546 A1	5/2006	Bergersen	
2006/0154198 A1	7/2006	Durbin et al.	
2006/0223032 A1	10/2006	Fried et al.	
2006/0223342 A1	10/2006	Borst et al.	
2006/0234179 A1	10/2006	Wen et al.	
2007/0046865 A1	3/2007	Umeda et al.	
2007/0053048 A1	3/2007	Kumar et al.	
2007/0087300 A1	4/2007	Willison et al.	
2007/0184402 A1	8/2007	Boutoussov et al.	
2007/0231765 A1	10/2007	Phan et al.	
2007/0296959 A1	12/2007	Schwotzer	
2008/0045053 A1	2/2008	Stadler et al.	
2008/0062429 A1	3/2008	Liang et al.	
2008/0063998 A1*	3/2008	Liang	A61B 1/0638 433/29
2008/0090208 A1	4/2008	Rubbert	
2008/0115791 A1	5/2008	Heine	
2008/0176448 A1	7/2008	Muller et al.	
2008/0242144 A1	10/2008	Dietz	
2009/0030347 A1	1/2009	Cao	
2009/0040740 A1	2/2009	Muller et al.	
2009/0061379 A1	3/2009	Yamamoto et al.	
2009/0061381 A1	3/2009	Durbin et al.	
2009/0075228 A1	3/2009	Kumada et al.	
2009/0210032 A1	8/2009	Beiski et al.	
2009/0218514 A1	9/2009	Klunder et al.	
2009/0298017 A1	12/2009	Boerjes et al.	
2009/0305540 A1	12/2009	Stadler et al.	
2010/0045902 A1	2/2010	Ikeda et al.	
2010/0085636 A1	4/2010	Berner	
2010/0152599 A1	6/2010	DuHamel et al.	
2010/0165275 A1	7/2010	Tsukamoto et al.	
2010/0167225 A1	7/2010	Kuo	
2010/0231577 A1	9/2010	Kim et al.	
2010/0312484 A1	12/2010	DuHamel et al.	
2011/0045428 A1	2/2011	Boltunov et al.	
2011/0081625 A1	4/2011	Fuh	
2011/0102549 A1	5/2011	Takahashi	
2011/0102566 A1	5/2011	Zakian et al.	
2011/0143673 A1	6/2011	Landesman et al.	
2011/0229840 A1*	9/2011	Liang	A61B 5/1077 433/29
2011/0235045 A1	9/2011	Koerner et al.	
2011/0269092 A1	11/2011	Kuo et al.	
2012/0081786 A1	4/2012	Mizuyama et al.	
2012/0086681 A1	4/2012	Kim et al.	
2012/0092461 A1	4/2012	Fisker et al.	
2012/0129117 A1	5/2012	McCance	
2012/0147912 A1	6/2012	Moench et al.	
2012/0172678 A1	7/2012	Logan et al.	
2012/0281293 A1	11/2012	Gronenborn et al.	
2012/0295216 A1	11/2012	Dykes et al.	
2012/0322025 A1	12/2012	Ozawa et al.	
2013/0089828 A1	4/2013	Borovinskih et al.	
2013/0095446 A1	4/2013	Andreiko et al.	

(56) **References Cited**

U.S. PATENT DOCUMENTS

2013/0103176 A1	4/2013	Kopelman et al.
2013/0110469 A1	5/2013	Kopelman
2013/0163627 A1	6/2013	Seurin et al.
2013/0201488 A1	8/2013	Ishihara
2013/0235165 A1	9/2013	Gharib et al.
2013/0252195 A1	9/2013	Popat
2013/0266326 A1	10/2013	Joseph et al.
2013/0280671 A1	10/2013	Brawn et al.
2013/0286174 A1	10/2013	Urakabe
2013/0293824 A1	11/2013	Yoneyama et al.
2013/0323664 A1	12/2013	Parker
2013/0323671 A1	12/2013	Dillon et al.
2013/0323674 A1	12/2013	Hakomori et al.
2014/0081091 A1	3/2014	Abolfathi et al.
2014/0272774 A1	9/2014	Dillon et al.
2014/0294273 A1	10/2014	Jaisson
2014/0313299 A1	10/2014	Gebhardt et al.
2014/0329194 A1	11/2014	Sachdeva et al.
2014/0363778 A1	12/2014	Parker
2015/0002649 A1	1/2015	Nowak et al.
2015/0029309 A1	1/2015	Michaeli et al.
2015/0079531 A1	3/2015	Heine
2015/0140502 A1	5/2015	Brawn et al.
2015/0164335 A1	6/2015	Van Der Poel et al.
2015/0173856 A1	6/2015	Lowe et al.
2015/0230885 A1	8/2015	Wucher
2015/0238280 A1	8/2015	Wu et al.
2015/0238283 A1	8/2015	Tanugula et al.
2015/0306486 A1	10/2015	Logan et al.
2015/0320320 A1	11/2015	Kopelman et al.
2015/0325044 A1	11/2015	Lebovitz
2015/0338209 A1	11/2015	Knuttel
2016/0000332 A1	1/2016	Atiya et al.
2016/0003610 A1	1/2016	Lampert et al.
2016/0045291 A1*	2/2016	Verker A61C 9/0066 356/364
2016/0051345 A1	2/2016	Levin
2016/0064898 A1	3/2016	Atiya et al.
2016/0067013 A1	3/2016	Morton et al.
2016/0081768 A1	3/2016	Kopelman et al.
2016/0081769 A1	3/2016	Kimura et al.
2016/0135924 A1	5/2016	Choi et al.
2016/0135925 A1	5/2016	Mason et al.
2016/0163115 A1	6/2016	Furst
2016/0217708 A1	7/2016	Levin et al.
2016/0296303 A1	10/2016	Parker
2016/0328843 A1	11/2016	Graham et al.
2016/0330355 A1	11/2016	Tchouprakov et al.
2017/0007366 A1	1/2017	Kopelman et al.
2017/0007367 A1	1/2017	Li et al.
2017/0049311 A1	2/2017	Borovinskih et al.
2017/0049326 A1	2/2017	Alfano et al.
2017/0056131 A1	3/2017	Alauddin et al.
2017/0156821 A1	6/2017	Kopelman et al.
2017/0265970 A1	9/2017	Verker et al.
2017/0325690 A1	11/2017	Salah et al.
2018/0000563 A1	1/2018	Shanjani et al.
2018/0000565 A1	1/2018	Shanjani et al.
2018/0028063 A1	2/2018	Elbaz et al.
2018/0028064 A1	2/2018	Elbaz et al.
2018/0028065 A1	2/2018	Elbaz et al.
2018/0055602 A1	3/2018	Kopelman et al.
2018/0125610 A1	5/2018	Carrier, Jr. et al.
2018/0153648 A1	6/2018	Shanjani et al.
2018/0153649 A1	6/2018	Wu et al.
2018/0153733 A1	6/2018	Kuo
2018/0280118 A1	10/2018	Cramer
2018/0284727 A1	10/2018	Cramer et al.

FOREIGN PATENT DOCUMENTS

AU	9150082 A	6/1984
AU	5598894 A	6/1994
CA	1121955 A1	4/1982
CN	102802520 A	11/2012
DE	2749802 A1	5/1978
DE	69327661 T2	7/2000
DE	102005043627 A1	3/2007
DE	202010017014 U1	3/2011
DE	102011051443 A1	1/2013
DE	102014225457 A1	6/2016
EP	0428152 A1	5/1991
EP	490848 A2	6/1992
EP	541500 A1	5/1993
EP	0714632 B1	5/1997
EP	774933 B1	12/2000
EP	731673 B1	5/2001
EP	1941843 A2	7/2008
EP	2213223 A1	8/2010
EP	2437027 A2	4/2012
EP	2447754 A1	5/2012
EP	1989764 B1	7/2012
EP	2332221 B1	11/2012
EP	2596553 B1	12/2013
EP	2612300 B1	2/2015
EP	2848229 A1	3/2015
ES	463897 A1	1/1980
ES	2455066 A1	4/2014
FR	2369828 A1	6/1978
FR	2930334 A1	10/2009
GB	1550777 A	8/1979
JP	H53-058191 A	5/1978
JP	04-258359 A	1/1992
JP	H08-508174 A	9/1996
JP	63-11148	1/1998
JP	2002-522752 A	7/2002
JP	2003290133 A	10/2003
JP	2007-260158 A	10/2007
JP	2008-523370 A	7/2008
JP	04184427 B1	11/2008
JP	2009-000412 A	1/2009
JP	2009-018173 A	1/2009
JP	2011-087733 A	5/2011
JP	2012-526977 A	11/2012
JP	2013-007645 A	1/2013
JP	2016528972 A	9/2016
KR	10-1266966 B1	5/2013
KR	10-2016-041632 A	4/2016
KR	10-2016-0071127 A	6/2016
WO	91-004713 A1	4/1991
WO	94-010935 A1	5/1994
WO	98-032394 A1	7/1998
WO	98-044865 A1	10/1998
WO	2000/08415 A1	2/2000
WO	2002-017776 A2	3/2002
WO	2002-062252 A1	8/2002
WO	2002-095475 A1	11/2002
WO	2003-003932 A2	1/2003
WO	2006-096558 A2	9/2006
WO	2006-133548 A1	12/2006
WO	2009-085752 A2	7/2009
WO	2009-089129 A1	7/2009
WO	2009-146788 A1	12/2009
WO	2009-146789 A1	12/2009
WO	2012-007003 A1	1/2012
WO	2012-064684 A2	5/2012
WO	2012-074304 A2	6/2012
WO	2014-091865 A1	6/2014
WO	2015/015289 A2	2/2015
WO	2015-015289 A2	2/2015
WO	2015-063032 A1	5/2015
WO	2015-176004 A1	11/2015
WO	2016-004415 A1	1/2016
WO	2016-042393 A1	3/2016
WO	2016-061279 A1	4/2016
WO	2016-084066 A1	6/2016
WO	2016-099471 A1	6/2016
WO	2016-113745 A1	7/2016

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

WO	2016-116874 A1	7/2016
WO	2018-085718 A2	5/2018

OTHER PUBLICATIONS

Kochanek et al., "Interpolating Splines with Local Tension, Continuity and Bias Control", Computer Graphics; 18(3); pp. 33-41; Jan. 1, 1984.
Kumar et al.; Rapid maxillary expansion: A unique treatment modality in dentistry; J. Clin. Diagn. Res.; 5(4); pp. 906-911; Aug. 2011.
Kunii et al., "Articulation Simulation for an Intelligent Dental Care System" Displays; 15(3); pp. 181-188; Jul. 1994.
Kuroda et al., "Three-Dimensional Dental Cast Analyzing System Using Laser Scanning", American Journal of Orthodontics and Dentofacial Orthopedics; 11 0(4); pp. 365-369; Oct. 1996.
Laurendeau et al., "A Computer-Vision Technique for the Acquisition and Processing of 3-D Profiles of Dental Imprints: An Application in Orthodontics", IEEE Transactions on Medical Imaging; 1 0(3); pp. 453-461; Sep. 1991.
Leinfelder et al., "A New Method for Generating Ceramic Restorations: a CAD-CAM System" Journal of the American Dental Association; 118(6); pp. 703-707; Jun. 1989.
Manetti et al., "Computer-Aided Cefalometry and New Mechanics in Orthodontics" Fortschr Kieferorthop; 44; pp. 370-376; 8 pages; (English Article Summary Included); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1983.
McCann; Inside the ADA; J. Amer. Dent. Assoc, 118:286-294; Mar. 1989.
McNamara et al., "Invisible Retainers", J. Clin Orthod.; pp. 570-578; 11 pages; (Author Manuscript); Aug. 1985.
McNamara et al.; "Orthodontic and Orthopedic Treatment in the Mixed Dentition", Needham Press; pp. 347-353; Jan. 1993.
Moermann et al, "Computer Machined Adhesive Porcelain Inlays: Margin Adaptation after Fatigue Stress", IADR Abstract 339; J. Dent. Res.; 66(a):763; (Abstract Only); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1987.
Moles, "Correcting Mild Malalignments—As Easy As One, Two, Three", AOA/Pro Corner; 11 (2); 2 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2002.
Mormann et al.; "Marginale Adaptation von adhasuven Porzellaninlays in vitro", Separatdruck aus:Schweiz. Mschr. Zahnmed.; 95; pp. 1118-1129: 8 pages; (Machine Translated English Abstract); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 1985.
Nahoum, "The Vacuum Formed Dental Contour Appliance", N.Y. State Dent. J.; 30(9); pp. 385-390; Nov. 1964.
Nash, "CEREC CAD/CAM Inlays: Aesthetics and Durability in a Single Appointment", Dentistry Today; 9(8); pp. 20, 22-23 and 54; Oct. 1990.
Nedelcu et al.; "Scanning Accuracy and Precision in 4 Intraoral Scanners: An In Vitro Comparison Based on 3-Dimensional Analysis"; J. Prosthet. Dent.; 112(6); pp. 1461-1471; Dec. 2014.
Nishiyama et al., "A New Construction of Tooth Repositioner by LTV Vinyl Silicone Rubber", Journal of Nihon University School of Dentistry; 19(2); pp. 93-102 (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1977.
Ogawa et al., "Mapping, profiling and clustering of pressure pain threshold (PPT) in edentulous oral muscosa", Journal of Dentistry; 32(3); pp. 219-228; Mar. 2004.
Ogimoto et al., "Pressure-pain threshold determination in the oral mucosa: validity and reliability", Journal of Oral Rehabilitation; 29(7); pp. 620-626; Jul. 2002.
Paul et al.; "Digital Documentation of Individual Human Jaw and Tooth Forms for Applications in Orthodontics; Oral Surgery and Forensic Medicine" Proc. of the 24th Annual Conf. of the IEEE Industrial Electronics Society (IECON '98); vol. 4; pp. 2415-2418; Sep. 4, 1998.
Pinkham, "'Foolish' Concept Propels Technology", Dentist, 3 pages, Jan./Feb. 1989.
Pinkham, "Inventor's CAD/CAM May Transform Dentistry", Dentist; pp. 1 and 35, Sep. 1990.
Ponitz, "Invisible Retainers", American Journal of Orthodics, 59(3); pp. 266-272; Mar. 1971.
Procera Research Projects; Procera Research Projects 1993. Abstract Collection; 23 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1993.
Proffit et al., "The First Stage of Comprehensive Treatment: Alignment and Leveling", Contemporary Orthodontics, 3rd Ed.; Chapter 16; Mosby Inc.; pp. 534-537; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2000.
Proffit et al.; "The First Stage of Comprehensive Treatment: Alignment and Leveling", Contemporary Orthodontics; (Second Ed.); Chapter 15, MosbyYear Book; St. Louis, Missouri; pp. 470-533 Oct. 1993.
Raintree Essix & ARS Materials, Inc., Raintree Essix, Technical Magazine Table of contents and Essix Appliances, 7 pages; retrieved from the internet (http:llwww.essix.com.lmagazineldefaulthtml) on Aug. 13, 1997.
Redmond et al.; "Clinical Implications of Digital Orthodontics", American Journal of Orthodontics and Dentofacial Orthopedics; 117(2); pp. 240-242; Feb. 2000.
Rekow et al., "CAD/CAM for Dental Restorations—Some of the Curious Challenges", IEEE Transactions on Biomedical Engineering; 38(4); pp. 314-318; Apr. 1991.
Rekow et al., "Comparison of Three Data Acquisition Techniques for 3-D Tooth Surface Mapping", Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 13(1); pp. 344-345 (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1991.
Rekow, "A Review of the Developments in Dental CAD/CAM Systems", Current Opinion in Dentistry; pp. 25-33; Jun. 1992.
Rekow, "CAD/CAM in Dentistry: A Historical Perspective and View of the Future", Journal Canadian Dental Association; 58(4); pp. 283, 287-288; Apr. 1992.
Rekow, "Computer-Aided Design and Manufacturing in Dentistry: A Review of the State of the Art", Journal of Prosthetic Dentistry; 58(4); pp. 512-516; Dec. 1987.
Rekow, "Dental CAD-CAM Systems: What is the State of the Art?", The Journal of the American Dental Association; 122(12); pp. 43-48; Dec. 1991.
Rekow, "Feasibility of an Automated System for Production of Dental Restorations", Ph.D. Thesis; Univ. of Minnesota, 250 pages, Nov. 1988.
Richmond et al., "The Development of a 3D Cast Analysis System", British Journal of Orthodontics; 13(1); pp. 53-54; Jan. 1986.
Richmond et al., "The Development of the PAR Index (Peer Assessment Rating): Reliability and Validity", The European Journal of Orthodontics; 41(2); pp. 125-139; Apr. 1992.
Richmond, "Recording the Dental Cast in Three Dimensions", American Journal of Orthodontics and Dentofacial Orthopedics; 92(3); pp. 199-206; Sep. 1987.
Rudge, "Dental Arch Analysis: Arch Form, A Review of the Literature" European Journal of Orthodontics; 3(4); pp. 279-284; Jan. 1981.
Sahm et al, "Micro-Electronic Monitoring of Functional Appliance Wear"; Eur J Orthod.; 12(3); pp. 297-301; Aug. 1990.
Sahm, "Presentation of a wear timer for the clarification of scientific questions in orthodontic orthopedics", Fortschritte der Kieferorthopadie; 51 (4); pp. 243-247; (Translation Included) Jul. 1990.
Sakuda et al. "Integrated Information-Processing System in Clinical Orthodontics: An Approach with Use of a Computer Network System", American Journal of Orthodontics and Dentofacial Orthopedics; 101 (3); pp. 210-220; 20 pages; (Author Manuscript) Mar. 1992.

(56) **References Cited**

OTHER PUBLICATIONS

Schafer et al.; "Quantifying patient adherence during active orthodontic treatment with removable appliances using microelectronic wear-time documentation"; Eur J Orthod.; 37(1) pp. 1-8; doi:10.1093/ejo/cju012; Jul. 3, 2014.
Schellhas et al., "Three-Dimensional Computed Tomography in Maxillofacial Surgical Planning", Archives of Otolaryngology—Head and Neck Surgery; 114(4); pp. 438-442; Apr. 1988.
Schroeder et al; Eds. "The Visual Toolkit", Prentice Hall PTR, New Jersey; Chapters 6, 8 & 9, (pp. 153-210,309-354, and 355-428; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1998.
Shilliday, "Minimizing finishing problems with the mini-positioner", American Journal of Orthodontics; 59(6); pp. 596-599; Jun. 1971.
Shimada et al.; Application of Optical Coherence Tomography (OCT) for Diagnosis of Caries, Cracks, and Defects of Restorations, Current Oral Health Reports; 2(2); pp. 73-80; Jun. 2015.
International Search Report and Written Opinion for PCT Application No. PCT/IB2015/054950 dated Apr. 1, 2016.
International Preliminary Report on Patentability and Written Opinion for International Application No. PCT/IB2015/054950 dated Jan. 10, 2017.
IP Australia, Examination Report No. 1 for Patent Application No. 2015287312 dated Jul. 31, 2017, 4 pages.2018, 5 pages.
IP Australia, Examination Report No. 2 for Patent Application No. 2015287312 dated Feb. 12, 2018, 4 pages.2018, 4 pages.
Canadian Intellectual Property Office, Office Action for Canadian Patent Application No. 2,949,448 dated Sep. 26, 2017, 3 pages.
Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated May 29, 2018.
Korean Intellectual Property Office, Notification of Reason for Refusal for Korean Patent Application No. 10-2017-7003299 dated Nov. 14, 2017, including English translation, 15 pages.
International Search Report and Written Opinion for International Patent Application No. PCT/US2018/013321 dated Apr. 26, 2018, 16 pages.
AADR, American Association for Dental Research; Summary of Activities; Los Angeles, CA; p. 195; Mar. 20-23, 1980.
Alcaniz et al., "An Advanced System for the Simulation and Planning of Orthodontic Treatments" Visualization in Biomedical Computing, 4th Intl. Conf, VBC '96, Sep. 22-25, 1996, pp. 511-520, Springer-Verlag, Hamburg, Germany.
Alexander et al., "The DigiGraph Work Station Part 2 Clinical Management", J. Clin. Orthod., Jul. 1990, 12 pages.
Allesee Orthodontic Appliances: "Important Tip About Wearing the Red White & Blue Active Clear Retainer System", Allesee Orthodontic Appliances—Pro Lab; 1 page; (year of pub. Sufficiently earlier than effecitve US filing date and any foreign priroirty date); 1998.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (Patient Information); retrieved from the internet (http://ormco.com/aoa/appliancesservices/RWB/patients.html); 2 pages on May 19, 2003.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (product information for doctors); retrieved from the internet (http://ormco.com/aoa/appliancesservices/RWB/doctrohtml); 5 pages on May 19, 2003.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (product information), 6 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 2003.
Allesee Orthodontic Appliances; The Red, White & Blue Way to Improve Your Smile; (information for patients), 2 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1992.
Allesee Orthodontic Appliances; You may be a candidate for this invisible no-braces treatment; product information for patients; 2 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 2002.
Allesee Orthodontic Applicances: Dura ClearTM; Product information; 1 page; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1997.
Altschuler et al., Analysis of 3-D Data for Comparative 3-D Serial Growth Pattern Studies of Oral-Facial Structures; IADR Abstracts, Program and Abstracts of Papers, 57th General Session, AIDR Annual Session, Mar. 29, 1979-Apr. 1, 1979, New Orleans Marriot; Journal of Dental Research; vol. 58, Special Issue A, p. 221; Jan. 1979.
Altschuler et al., Laser Electro-Optic System for Rapid Three-Dimensional (3D) Topographic Mapping of Surfaces; Optical Engineering; Dec. 1981, pp. 953-961, vol. 20(6).
Altschuler et al., "Measuring Surfaces Space-Coded by a Laser-Projected Dot Matrix" SPIE Imaging Applications for Automated Industrial Inspection and Assembly; Oct. 10, 1979, pp. 187-191, vol. 182.
Altschuler; 3D Mapping of Maxillo-Facial Prosthesis; AADR Abstract #607; 1 page, (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1980.
Andersson et al.; Clinical Results with Titanium Crowns Fabricated with Machine Duplication and Spark Erosion; Acta Odontologica Scandinavica; 47(5); pp. 279-286; Oct. 1989.
Andrews, "The Six Keys to Optimal Occlusion" Straight Wire, Chapter 3, L.A. Wells; pp. 13-24; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1989.
Barone et al., "Creation of 30 Multi-Body Orthodontic Models by Using Independent Imaging Sensors"; Sensors; 13(2); pp. 2033-2050; Feb. 5, 2013.
Bartels et al.; An Introduction to Splines for Use in Computer Graphics and Geometric Modeling; Morgan Kaufmann Publishers; pp. 422-425 Jan. 1, 1987.
Baumrind et al, "Mapping the Skull in 3-D," reprinted from J. Calif. Dent. Assoc, 48(2), 11 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) Fall Issue 1972, vol. 48, No. 2.
Baumrind et al., "A Stereophotogrammetric System for the Detection of Prosthesis Loosening in Total Hip Arthroplasty", NATO Symposium on Applications of Human Biostereometrics; SPIE; vol. 166; pp. 112-123; Jul. 9-13, 1978.
Baumrind, "A System for Crania facial Mapping Through the Integration of Data from Stereo X-Ray Films and Stereo Photographs", an invited paper submitted to the 1975 American Society of Photogram Symposium on Close-Range Photogram Systems; University of Illinois; pp. 142-166; Aug. 26-30, 1975.
Baumrind, "Integrated Three-Dimensional Craniofacial Mapping: Background, Principles, and Perspectives", Seminars in Orthodontics; 7(4); pp. 223-232; Dec. 2001.
Begole et al.; A Computer System for the Analysis of Dental Casts; The Angle Orthodontist; 51(3); pp. 252-258, Jul. 1981.
Bernard et al, "Computerized Diagnosis in Orthodontics for Epidemiological Studies: A ProgressReport" (Abstract Only), J. Dental Res. Special Issue, vol. 67, p. 169, paper presented at International Association for Dental Research 66th General Session, Montreal Canada; Mar. 9-13, 1988.
Bhatia et al., "A Computer-Aided Design for Orthognathic Surgery", British Journal of Oral and Maxillofacial Surgery; 22(4); pp. 237-253; Aug. 1, 1984.
Biggerstaff et al., "Computerized Analysis of Occlusion in the Postcanine Dentition", American Journal of Orthodontics; 61 (3); pp. 245-254; Mar. 1972.
Biggerstaff, "Computerized Diagnostic Setups and Simulations", Angle Orthodontist; 40(I); pp. 28-36; Jan. 1970.
Biostar Operation & Training Manual. Great Lakes Orthodontics, Ltd. 199 Fire Tower Drive, Tonawanda, New York. 14150-5890, 20 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1990.
Blu et al.; "Linear Interpolation Revitalized", IEEE Transactions on Image Processing; 13(5); pp. 710-719; May 2004.
Bourke, "Coordinate System Transformation", 2 pages, Jun. 1996, retrieved from the internet (http://local.wasp.uwa.edu.au/~pbourke/protection/coords/) on Sep. 19, 2006.

(56) **References Cited**

OTHER PUBLICATIONS

Boyd et al., "Three Dimensional Diagnosis and Orthodontic Treatment of Complex Malocclusions With the Invisalipn Appliance", Seminars in Orthodontics; 7(4); pp. 274-293; Dec. 2001.
Brandestini et al. "Computer Machined Ceramic Inlays: In Vitro Marginal Adaptation", J. Dent. Res. Special Issue; (Abstract 305); vol. 64; p. 208; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1985.
Brook et al., "An Image Analysis System for the Determination of Tooth Dimensions from Study Casts: Comparison with Manual Measurements of Mesio-distal Diameter", Journal of Dental Research; 65(3); pp. 428-431: Mar. 1986.
Burstone et al., "Precision Adjustment of the Transpalatal Lingual Arch: Computer Arch Form Predetermination", American Journal of Orthodontics; 79(2);pp. 115-133; Feb. 1981.
Burstone; "Dr. Charles J. Burstone on the Uses of the Computer in Orthodontic Practice (Part 1)"; Journal of Clinical Orthodontics; 13(7); pp. 442-453; (interview); Jul. 1979.
Burstone; "Dr. Charles J. Burstone on The Uses of the Computer in Orthodontic Practice (Part 2)"; Journal of Clinical Orthodontics; 13(8); pp. 539-551 (interview); Aug. 1979.
"Cardinal Industrial Finishes for Liquid and Powder Coatings", The Powder Coating Isntitute; 6 pages; retrieved from the internet (http://www.cardinalpaint.com/powder%20coatings.htm) on Aug. 25, 2000.
Carnaghan et al., "An Alternative to Holograms for the Portrayal of Human Teeth", 4th Int'l. Conf. on Holographic Systems, Components and Applications; pp. 228-231; Sep. 15, 1993.
Chaconas et al, "The DigiGraph Work Station, Part 1, Basic Concepts"; Journal of Clinical Orthodontics; 24(6); pp. 360-367; (Author Manuscript); Jun. 1990.
Chafetz et al., "Subsidence of the Femoral Prosthesis, A Stereophotogrammetric Evaluation", Clinical Orthopaedics and Related Research; No. 201; pp. 60-67; Dec. 1985.
Chiappone, "Constructing the Gnathologic Setup and Positioner", Journal of Clinical Orthodontics; 14(2); pp. 121-133; Feb. 1980.
Siemens; Cerec—"Computer-Reconstruction, High Tech in der Zahnmedizin", 15 pages; (Includes Machine Translation); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 2004.
Sinclair, "The Readers' Corner", Journal of Clinical Orthodontics; 26(6); pp. 369-372; 5 pages; retrived from the internet (http://www.jco-online.comlarchive/print_article .asp?Year= 1992&Month=06 &ArticleNum=); Jun. 1992.
Stoll et al.; "Computer-aided Technologies in Dentistry", Dtsch Zahna'rztl Z 45, pp. 314-322; (English Abstract Included); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1990.
Sturman, "Interactive Keyframe Animation of 3-D Articulated Models", Proceedings Graphics Interface '84; vol. 86; pp. 35-40; May-Jun. 1984.
The American Heritage, Stedman's Medical Dictionary; "Gingiva"; 3 pages; retrieved from the interent (http://reference.com/search/search?q=gingiva) on Nov. 5, 2004.
The Dental Company Sirona, "Cerec Omnicam and Cerec Bluecam. The first choice in every case", product brochure, 8 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2014.
Thera Mon; "Microsensor"; "2 pages"; retrieved from the internet (www.english.thera-mon.com/the-product/transponder/index.html); on Sep. 19, 2016.
Thorlabs; Pellin broca prisms; 1 page; retrieved from the internet (www.thorlabs.com); Nov. 30, 2012.
Truax, "Truax Clasp-Less(TM) Appliance System", The Functional Orthodontist; 9(5); pp. 22-24, 26-28; Sep.-Oct. 1992.
Tru-Tatn Orthodontic & Dental Supplies, Product Brochure, Rochester, Minnesota 55902, 16 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1996.
U.S. Department of Commerce, National Technical Information Service, "Holodontography: An Introduction to Dental Laser Holography", School of Aerospace Medicine Brooks AFB Tex; Mar. 1973, 37 pages.
Schmidt, et al. "Automated Crown Replication Using Solid Photography SM", National Technical Information Service, Solid Photography Inc., Melville NY,; Oct. 1977; 19 pages.
Van Der Linden, "A New Method to Determine Tooth Positions and Dental Arch Dimensions", Journal fo Dental Research; 51(4); p. 1104; Jul.-Aug. 1972.
Van Der Linden et al, "Three-Dimensional Analysis of Dental Casts by Means of the Optocom", Journal of Dental Research; 51 (4); p. 11 00; Jul.-Aug. 1972.
Van Der Zel, "Ceramic-Fused-to-Metal Restorations with a New CAD/Cam System", Quintessence International; 24 (A); pp. 769-778; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date); 1993.
Van Hilsen et al., "Comparing potential early caries assessment methods for teledentistry", BMC Oral Health; 13(16); doi: 101186/1472-6831-13-16; 9 pages; Mar. 2013.
Varady et al.; "Reverse Engineering of Geometric Models—An Introduction", Computer-Aided Design; 29(4); pp. 255-268; 29 pages; (Author Manuscript); May 13, 1996.
Verstreken et al., "An Image-Guided Planning System for Endosseous Oral Implants", IEEE Transactions on Medical Imaging; 17(5); pp. 842-852; Oct. 1998.
Warunek et al., "Physical and Mechanical Properties of Elastomers in Orthodonic Positioners", American Journal of Orthodontics and Dentofacial Orthopedics; 95(5); pp. 388-400; 21 pages; (Author Manuscript); May 1989.
Warunek et.al., "Clinical Use of Silicone Elastomer Applicances", JCO; 23 (10); pp. 694-700; Oct. 1989.
Wells, "Application of the Positioner Appliance in Orthodontic Treatment", American Journal of Orthodontics; 58(4); pp. 351-366; Oct. 1970.
Wishan, "New Advances in Personal Computer Applications for Cephalometric Analysis, Growth Prediction, Surgical Treatment Planning and Imaging Processing", Symposium: Computerized Facial Imaging in Oral and Maxilofacial Surgery; p. 5; Presented on Sep. 13, 1990.
Wikipedia; Palatal expansion; 3 pages; retrieved from the internet (https://en.wikipedia.org/wiki/Palatal_expansion) on Mar. 5, 2018.
Williams, "Dentistry and CAD/Cam: Another French Revolution", J. Dent. Practice Admin.; 4(1); pp. 2-5 Jan./Mar. 1987.
Williams, "The Switzerland and Minnesota Developments in CAD/CAM", Journal of Dental Practice Administration; 4(2); pp. 50-55; Apr./Jun. 1987.
Wireless Sensor Networks Magazine, "Embedded Teeth for Oral Activity Recognition", Jul. 29, 2013, 2 pages; retrieved on Sep. 19, 2016 from the internet (www.wsnmagazine.com/embedded-teeth/).
Witt et al., "The wear-timing measuring device in orthodontics—cui bono? Reflections on the state-of-the-art in wear-timing measurement and compliance research in orthodontics"; Fortschr Kieferothop; 52(3); pp. 117-125; (Translation Included) Jun. 1991.
WSCG'98—Conference Program, The Sixth International Conference in Central Europe on Computer Graphics and Visualization '98; pp. 1-7; retrieved from the Internet on Nov. 5, 2004, (http://wscg.zcu.cz/wscg98/wscg98.htm); Feb. 9-13, 1998.
Xia et al., "Three-Dimensional Virtual-Reality Surgical Planning and Soft-Tissue Prediction for Orthognathic Surgery", IEEE Transactions on Information Technology in Biomedicine; 5(2); pp. 97-107; Jun. 2001.
Yamada et al., "Simulation of fan-beam type optical computer-tomography imaging of strongly scattering and weakly absorbing media", Applied Optics; 32(25); pp. 4808-4814; Sep. 1, 1993.
Yamamoto et al., "Optical Measurement of Dental Cast Profile and Application to Analysis of Three-Dimensional Tooth Movement in Orthodontics", Front. Med. Biol. Eng., 1(2); pp. 119-130; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 1988.
Yamamoto et al., "Three-Dimensional Measurement of Dental Cast Profiles and Its Applications to Orthodontics", Conf. Proc. IEEE Eng. Med. Bioi. Soc.; 12(5); pp. 2052-2053; Nov. 1990.

(56) **References Cited**

OTHER PUBLICATIONS

Yamany et al., "A System for Human Jaw Modeling Using Intra-Oral Images", Proc. of the 20th Annual Conf. of the IEEE Engineering in Medicine and Biology Society; vol. 2; pp. 563-566; Oct. 1998.

Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); I. The D.P. Concept and Implementation of Transparent Silicone Resin (Orthocon)"; Nippon Dental Review; 452; pp. 61-74; 32 pages; (Author Manuscript); Jun. 1980.

Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); II. The D.P. Manufacturing Procedure and Clinical Applications", Nippon Dental Review; 454; pp. 107-130; 48 pages; (Author Manuscript); Aug. 1980.

Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.)—III. The General Concept of the D.P. Method and Its Therapeutic Effect, Part 1, Dental and Functional Reversed Occlusion Case Reports", Nippon Dental Review; 457; pp. 146-164; 43 pages; (Author Manuscript); Nov. 1980.

Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); III—The General Concept of the D.P. Method and Its Therapeutic Effect, Part 2. Skeletal Reversed Occlusion Case Reports", Nippon Dental Review; 458; pp. 112-129; 40 pages; (Author Manuscript); Dec. 1980.

Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated Dec. 18, 2018.

Park, H. et al. "Development of High Speed and High Accuracy 3D Dental Intra Oral Scanner," Procedia Eng. 100 (2015) 1174-1181.

Third-Party Submission Under 37 CFR 1.290 for U.S. Appl. No. 15/859,010, filed Jan. 11, 2019.

International Search Report and Written Opinion for PCT Application No. PCT/IB2015/001400 dated Feb. 9, 2016, 18 pages.

Tiziani H. J. et al., "Confocal principle for macro- and microscopic surface and defect analysis," Optical Engineering, Jan. 1, 2000, pp. 32-39, vol. 39(1), Society of Photo-Optical Instrumentation Engineers.

Chishti et al.; U.S. Appl. No. 60/050,342 entitled "Procedure for Moving Teeth Using a Seires of Retainers," filed Jun. 20, 1997.

Cottingham, "Gnathologic Clear Plastic Positioner", American Journal of Orthodontics; 55(1); pp. 23-31; Jan. 1969.

Crawford; CAD/CAM in the Dental Office: Does It Work?; Canadian Dental Journal; 57(2); pp. 121-123 Feb. 1991.

Crawford, Computers in Dentistry: Part 1: CAD/CAM: The Computer Moves Chairside, Part 2: F. Duret—A Man With a Vision, Part 3: The Computer Gives New Vision—Literally, Part 4: Bytes 'N Bites The Computer Moves From The Front Desk to The Operatory; Canadian Dental Journal; 54(9); pp. 661-666 Sep. 1988.

Crooks; CAD/CAM Comes to USC; USC Dentistry; pp. 14-17; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) Spring 1990.

Cureton, "Correcting Malaligned Mandibular Incisors with Removable Retainers", Journal of Clinical Orthodontics; 30(7); pp. 390-395; Jul. 1996.

Curry et al., "Integrated Three-Dimensional Craniofacial Mapping at the Craniofacial Research Instrumentation Laboratory / University of the Pacific", Seminars in Orthodontics; 7(4); pp. 258-265; Dec. 2001.

Cutting et al., "Three-Dimensional Computer-Assisted Design of Craniofacial Surgical Procedures: Optimization and Interaction with Cephalometric and CT-Based Models", Plastic and Reconstructive Surgery; 77(6); pp. 877-885; Jun. 1986.

DCS Dental AG; The CAD/CAM 'DCS Titan System' for Production of Crowns/Bridges; DSC Production; pp. 1-7; Jan. 1992.

Defranco et al., "Three-Dimensional Large Displacement Analysis of Orthodontic Appliances", Journal of Biomechanics; 9(12); pp. 793-801; Jan. 1976.

Dental Institute University of Zurich Switzerland; Program for International Symposium on Computer Restorations: State of the Art of the CEREC-Method; 2 pages; May 1991.

Dentrac Corporation; Dentrac document; pp. 4-13; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1992.

Dent-X; "DentSim . . . Dent-x's virtual reality 3-D training simulator . . . A revolution in dental education", 6 pages; retrieved from the internet (http://www.dent-x.com/DentSim.htm); on Sep. 24, 1998.

Doruk et al., "The role of the headgear timer in extraoral co-operation", European Journal of Orthodontics; 26; pp. 289-291; Jun. 1, 2014.

Doyle; "Digital Dentistry, Doctors use CAD/CAM to take the pain out of extensive dental procedures", Computer Graphics World; pp. 50-52 and p. 54; Oct. 2000.

Dummer et al., "Computed Radiography Imaging Based on High-Density 670 nm VCSEL Arrays", International Society for Optics and Photonics; vol. 7557, p. 7557OH, 7 pages; (Author Manuscript); Feb. 24, 2010.

Duret et al., "CAD/CAM Imaging in Dentistry", Current Opinion in Dentistry; 1 (2); pp. 150-154; Apr. 1991.

Duret et al; CAD-CAM in Dentistry; Journal of the American Dental Association; 117(6); pp. 715-720; Nov. 1988.

Duret, "The Dental CAD/CAM, General Description of the Project", Hennson International Product Brochure, 18 pages; Jan. 1986.

Duret; Vers Une Prosthese Informatisee; Tonus; 75(15); pp. 55-57; (English translation attached); 23 pages; Nov. 15, 1985.

Economides, "The Microcomputer in the Orthodontic Office", Journal of Clinical Orthodontics; 13(11); pp. 767-772; Nov. 1979.

Elsasser, "Some Observations on the History and Uses of the Kesling Positioner", American Journal of Orthodontics; 36(5); pp. 368-374; May 1, 1950.

Faber et al., "Computerized Interactive Orthodontic Treatment Planning", American Journal of Orthodontics; 73(1); pp. 36-46; Jan. 1978.

Felton et al., "A Computerized Analysis of the Shape and Stability of Mandibular Arch Form", American Journal of Orthodontics and Detofacial Orthopedics, Dec. 1987, pp. 478-483, vol. 92 No. 6, The C. V. Mosby Company.

Friede et al., "Accuracy of Cephalometric Prediction in Orthognathic Surgery", Journal of Oral and Maxillofacial Surgery; 45(9); pp. 754-760; Sep. 1987.

Friedrich et al; "Measuring system for in vivo recording of force systems in orthodontic treatment-concept and analysis of accuracy", J. Biomech.; 32(1); pp. 81-85; (Abstract only) Jan. 1999.

Futterling et al, "Automated Finite Element Modeling of a Human Mandible with Dental Implants", JS WSCG '98—Conference Program; 8 pages; retrieved from the Internet (https://dspace5.zcu.cz/bitstream/11025/15851/1/Strasser_98.pdf); on Aug. 21, 2018.

Gao et al., "3-D Element Generation for Multi-Connected Complex Dental and Mandibular Structure", IEEE Proceedings International Workshop in Medical Imaging and Augmented Reality; pp. 267-271; Jun. 12, 2001.

Gim-Alldent Deutschland, "Das DUX System: Die Technik," 3 pages; (English Translation Included}; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 2002.

Gottleib et al., JCO Interviews Dr. James A. McNamura, Jr., on the Frankel Appliance: Part 2: Clinical Management:, Joumal of Clinical Orthodontics; 16(6), Jun. 1982, pp. 390-407; retrieved from the internet (http://www .jco-online.com/archive/print_article.asp?Year=1982&Month=06&ArticleNum+) on Mar. 9, 2005.

Grayson, "New Methods for Three Dimensional Analysis of Craniofacial Deformity", Symposium: Computerized Facial Imaging in Oral and Maxillofacial Surgery; American Association of Oral and Maxillofacial Surgeons; 48(8) suppl 1; pp. 5-6; Sep. 13, 1990.

Grest, Daniel, Marker-Free Human Motion Capture in Dynamic Cluttered Environments from a Single View-Point:, PhD Thesis; 167 pages; Dec. 2007, Kiel, Germany.

Guess et al. "Computer Treatment Estimates in Orthodontics and Orthognathic Surgery" Journal of Clinical Orthodontics; 23(4); pp. 262-268; 11 pages; (Author Manuscript); Apr. 1989.

(56) **References Cited**

OTHER PUBLICATIONS

Heaven et al.; Computer-Based Image Analysis of Artificial Root Surface Caries; Abstracts of Papers #2094; Journal of Dental Research; vol. 70, Special Issue; p. 528; (Abstract Only); Apr. 17-21, 1991.

Highbeam Research, "Simulating stress put on jaw. (ANSYS Inc.'s finite element analysis software)" Nov. 1, 1996, 2 pages; retrieved from the Internet (http://static.highbeam.eom/titoolingampproduction/november011996/simulatingstressputonfa . . .); on Nov. 5, 2004.

Hikage, "Integrated Orthodontic Management System for Virtual Three-Dimensional Computer Graphic Simulation and Optical Video Image Database for Diagnosis and Treatment Planning" Journal of Japan KA Orthodontic Society; 46(2); pp. 248-269; 56 pages; (English Translation Included); Feb. 26, 1987.

Hoffmann et al., "Role of Cephalometry for Planning of Jaw Orthopedics and Jaw Surgery Procedures", Informatbnen, pp. 375-396; (English Abstract Included); Mar. 1991.

Hojjatie et al., Three-Dimensional Finite Element Analysis of Glass-Ceramic Dental Crowns; Journal of Biomechanics; 23(11); pp. 1157-1166; Jan. 1990.

Huckins, "CAD-CAM Generated Mandibular Model Prototype from MRI Data", AAOMS, p. 96; (Abstract Only); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1999.

Invisalign; "You were made to move. There's never been a better time to straighten your teeth with the most advanced clear aligner in the world"; Product webpage; 2 pages; retrieved from the internet (www.invisalign.com/) on Dec. 28, 2017.

JCO Interviews, "Craig Andreiko , DDS, MS on the Elan and Orthos Systems; Interview by Dr. Larry W. White", Journal of Clinical Orthodontics; 28(8); pp. 459-468; 14 pages; (Author Manuscript); Aug. 1994.

JCO Interviews; "Dr. Horner W. Phillips on Computers in Orthodontic Practice, Part 2", Journal of Clinical Orthodontics; 17(12); pp. 819-831; 19 pages; Dec. 1983.

Jerrold, "The Problem, Electronic Data Transmission and the Law", American Journal of Orthodontics and Dentofacial Orthopedics; 113(4); 5 pages; (Author Manuscript); Apr. 1998.

Jones et al.; An Assessment of the Fit of a Parabolic Curve to Pre- and Post-Treatment Dental Arches; British Journal of Orthodontics; 16(2); pp. 85-93; May 1989.

Kamada et al., "Case reports on Tooth Positioners Using LTV Vinyl Silicone Rubber", J. Nihon University School of Dentistry; 26(1); pp. 11-29; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1984.

Kamada et al. "Construction of Tooth Positioners with OTV Vinyl Silicone Rubber and Some Case Reports", J. Nihon University School of Dentistry; 24(1); pp. 1-27; (year of pub. Sufficiently earlier than effective US filing date anda ny foreign priority date) 1982.

Kanazawa et al., "Three-Dimensional Measurements of the Occlusal Surfaces of Upper Molars in a Dutch Population", Journal of Dental Research; 63(11); pp. 1298-1301; Nov. 1984.

Kesling et al., "The Philosophy of the Tooth Positioning Appliance", American Journal of Orthodontics and Oral Surgery; 31 (6); pp. 297-304; Jun. 1945.

Kesling, "Coordinating the Predetermined Pattern and Tooth Positioner with Conventional Treatment", American Journal of Orthodontics and Oral Surgery; 32(5); pp. 285-293; May 1946.

Office Action for Chinese Patent Application No. 201580056255.2 dated Jan. 16, 2019,Chinese only, 7 pages.

Office Action for Chinese Patent Application No. 201580037043.X dated Jan. 2, 2019, with English translation, 18 pages.

Second Office Action for Chinese Patent Application No. 201580037043.X dated Jun. 19, 2019, with English translation, 22 pages.

Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated Jun. 11, 2019, with English translation, 6 pages.

* cited by examiner

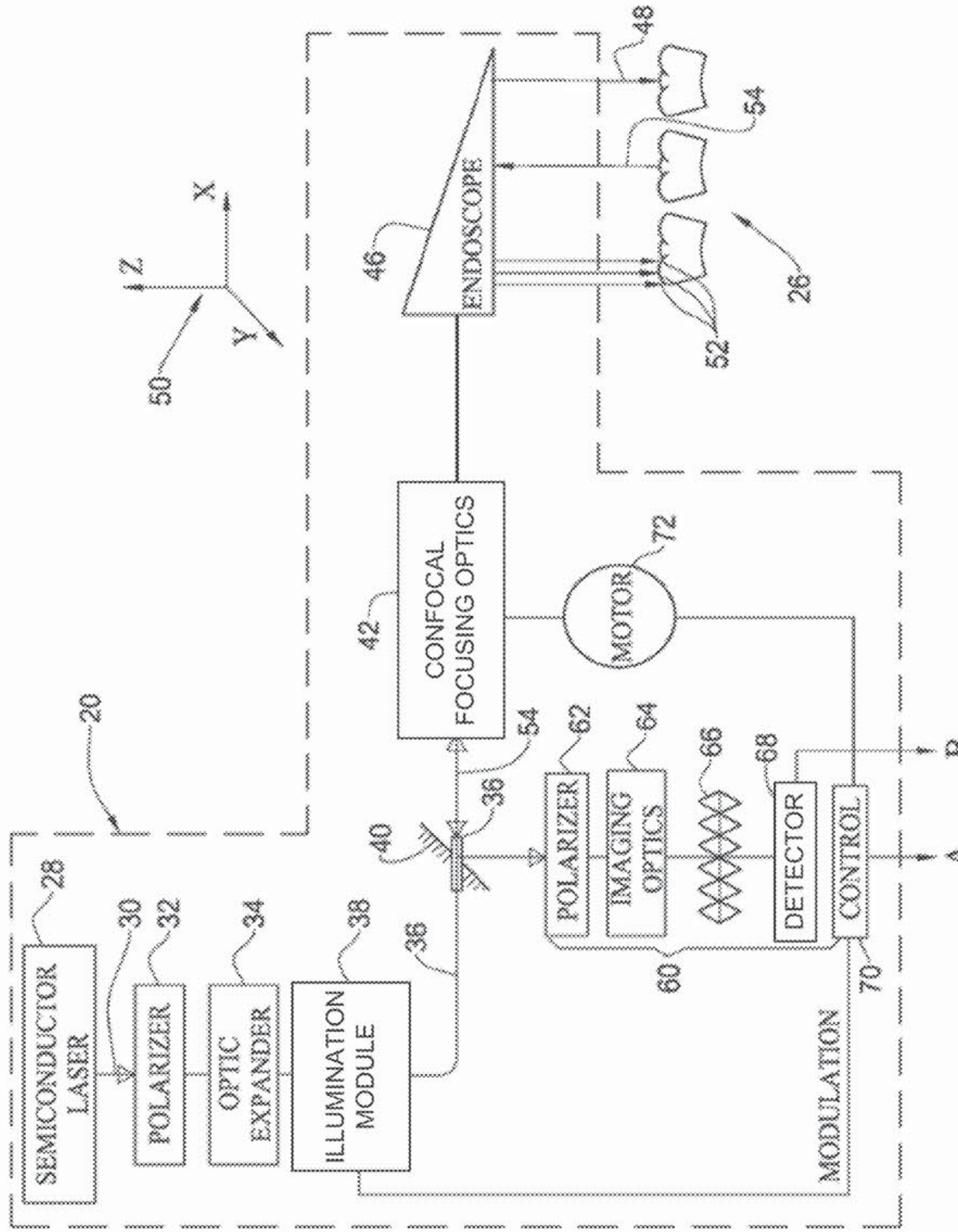

SEMICONDUCTOR LASER
POLARIZER
OPTIC EXPANDER
ILLUMINATION MODULE
CONFOCAL FOCUSING OPTICS
ENDOSCOPE
MOTOR
POLARIZER
IMAGING OPTICS
DETECTOR
CONTROL
MODULATION
A
B
X
Y
Z
20
26
28
30
32
34
36
38
40
42
46
48
50
52
54
60
62
64
66
68
70
72

FIG. 1A

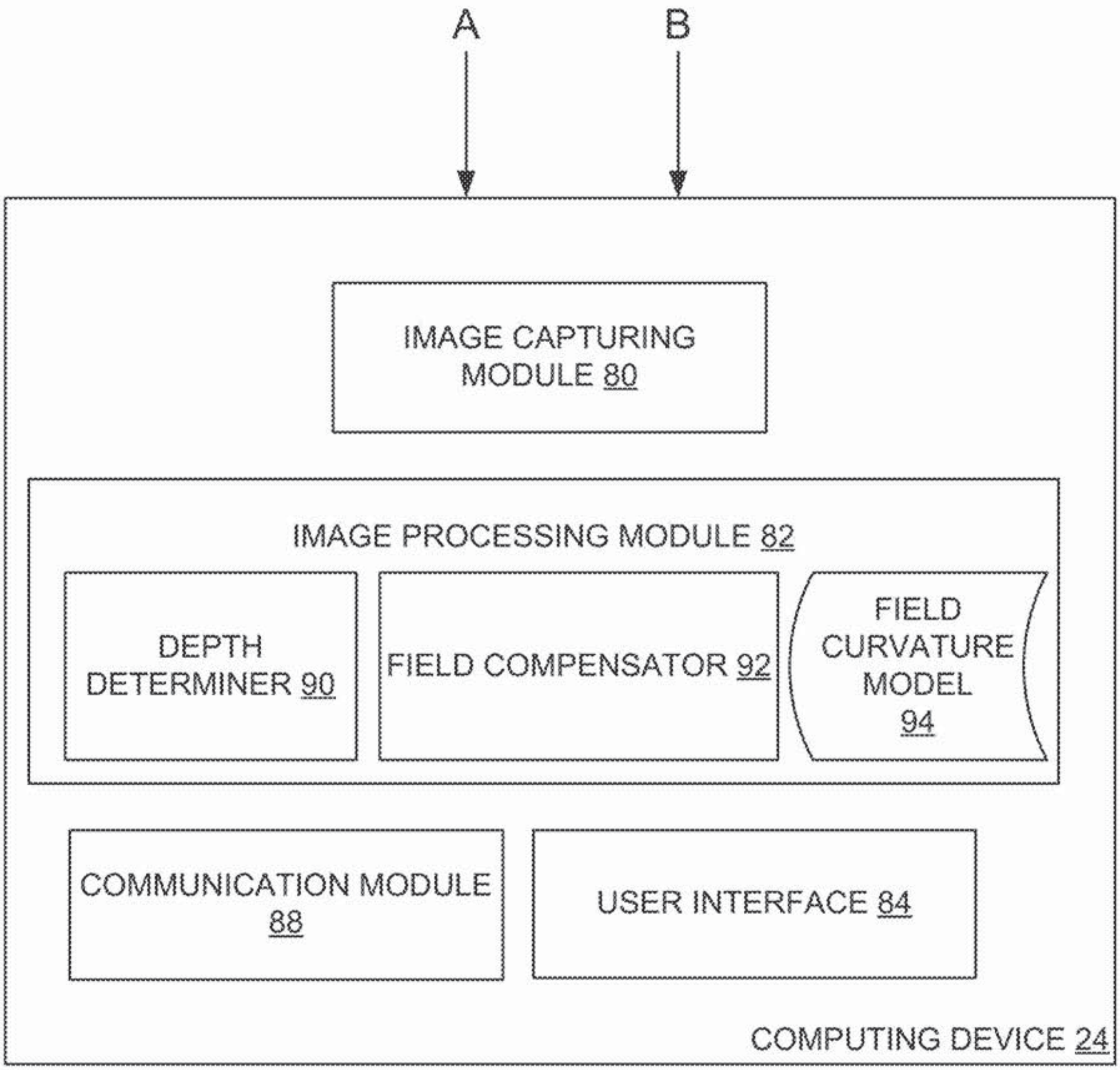

A
B
IMAGE CAPTURING MODULE 80
IMAGE PROCESSING MODULE 82
DEPTH DETERMINER 90
FIELD COMPENSATOR 92
FIELD CURVATURE MODEL 94
COMMUNICATION MODULE 88
USER INTERFACE 84
COMPUTING DEVICE 24

FIG. 1B

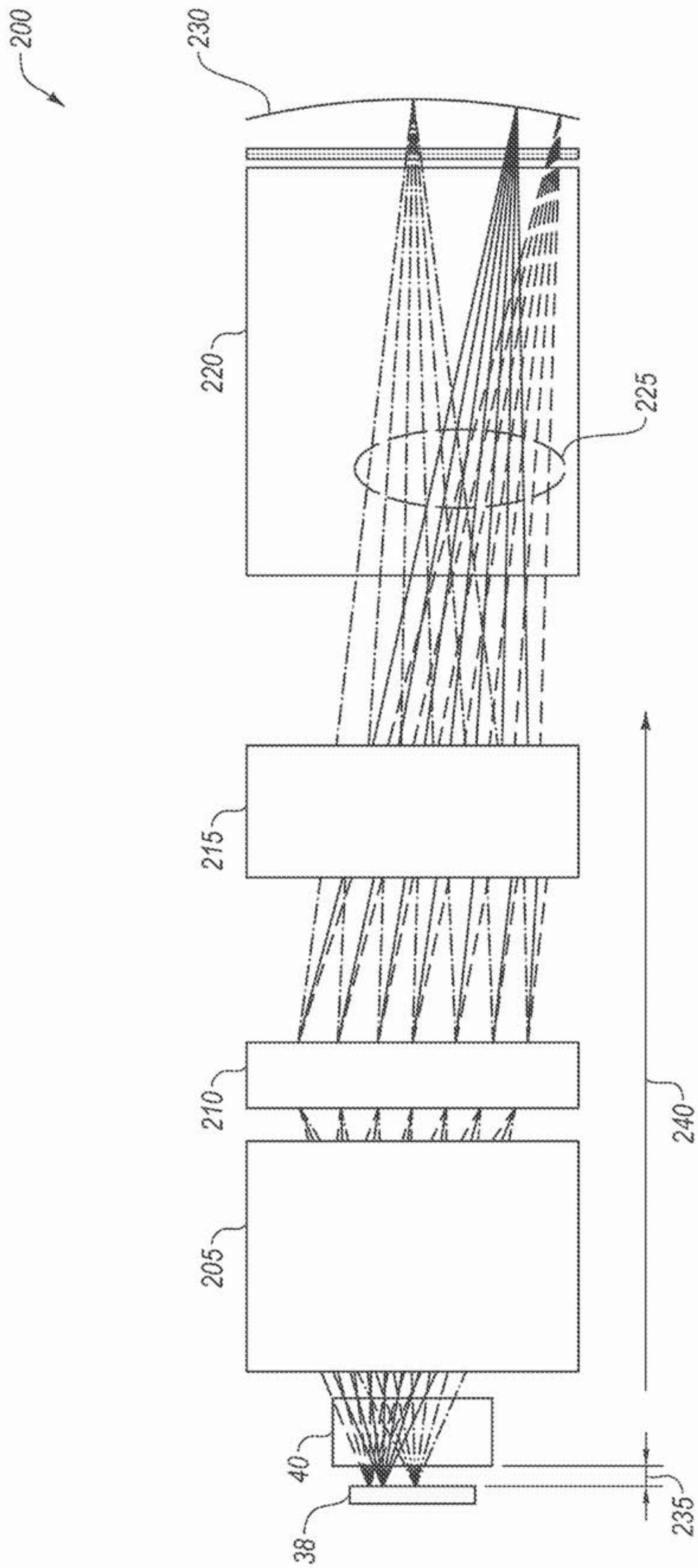


FIG. 2A

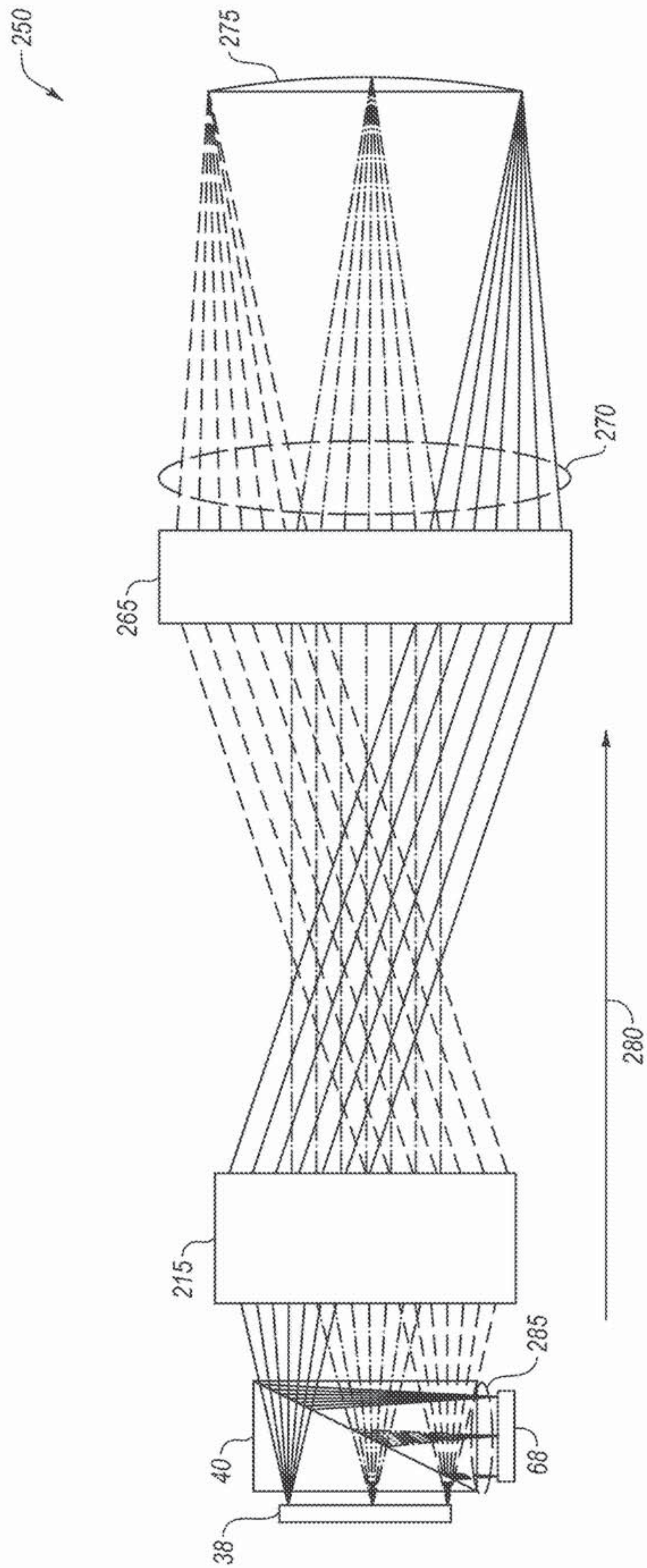


FIG. 2B

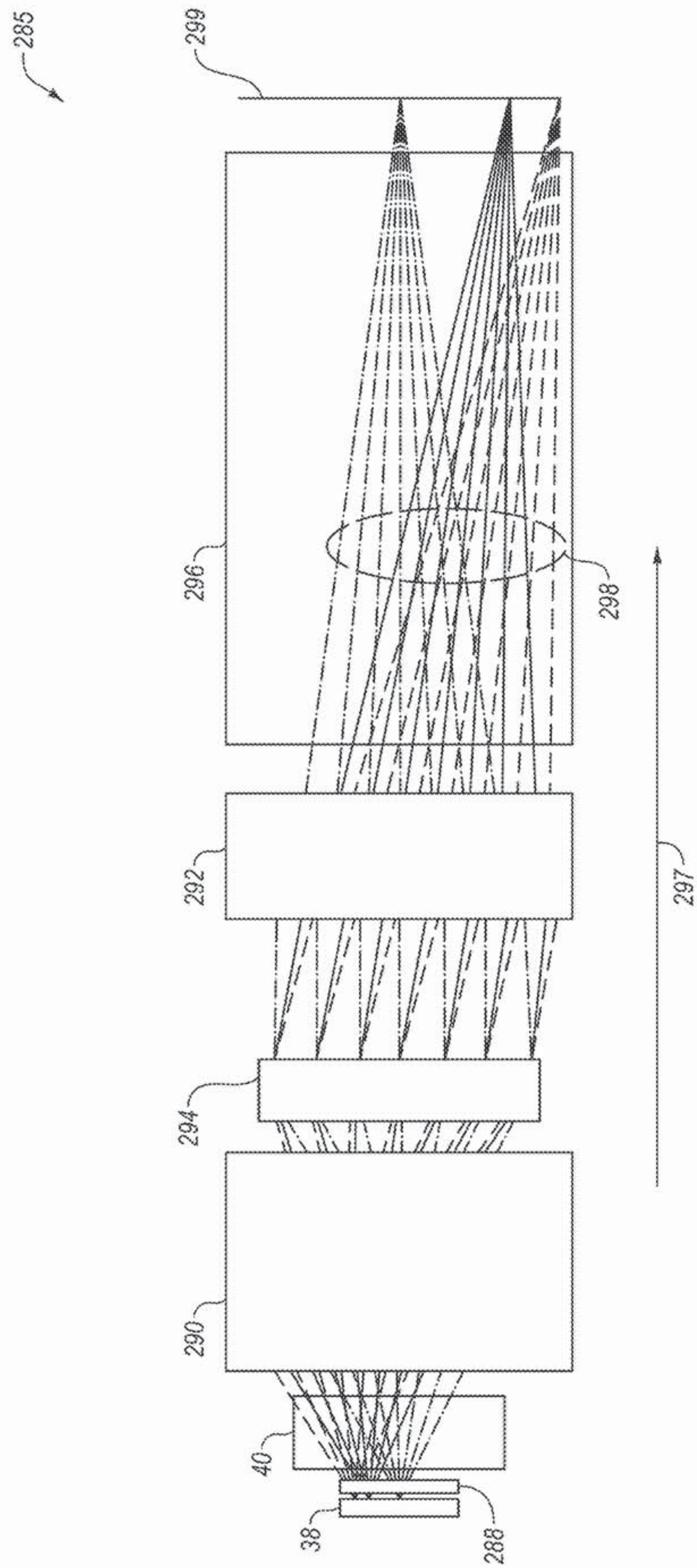


FIG. 2C

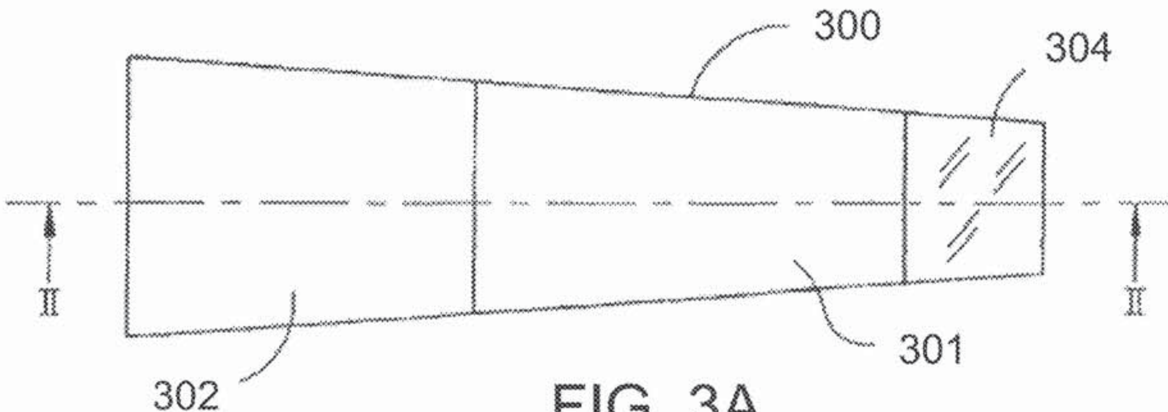

300
304
II
II
302
301

FIG. 3A

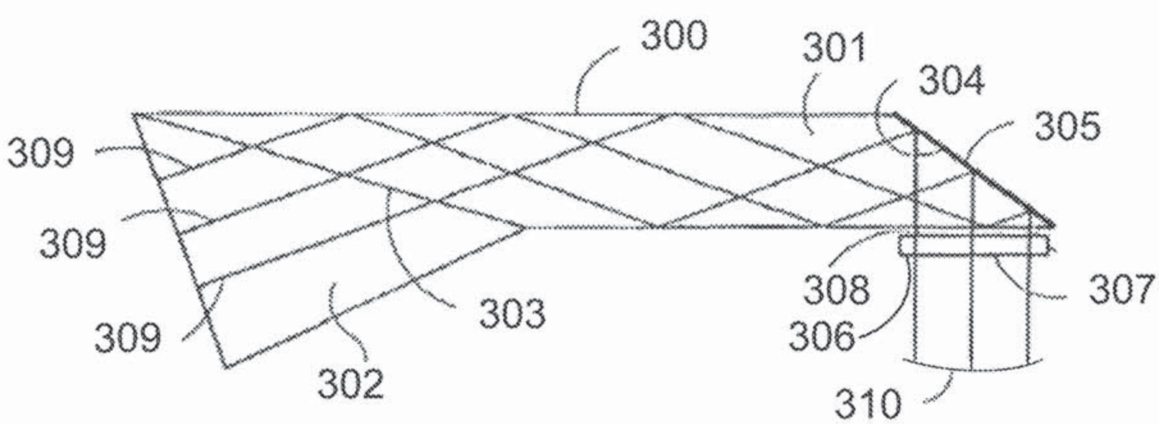

300
301
304
305
309
309
309
303
308
306
307
302
310

FIG. 3B

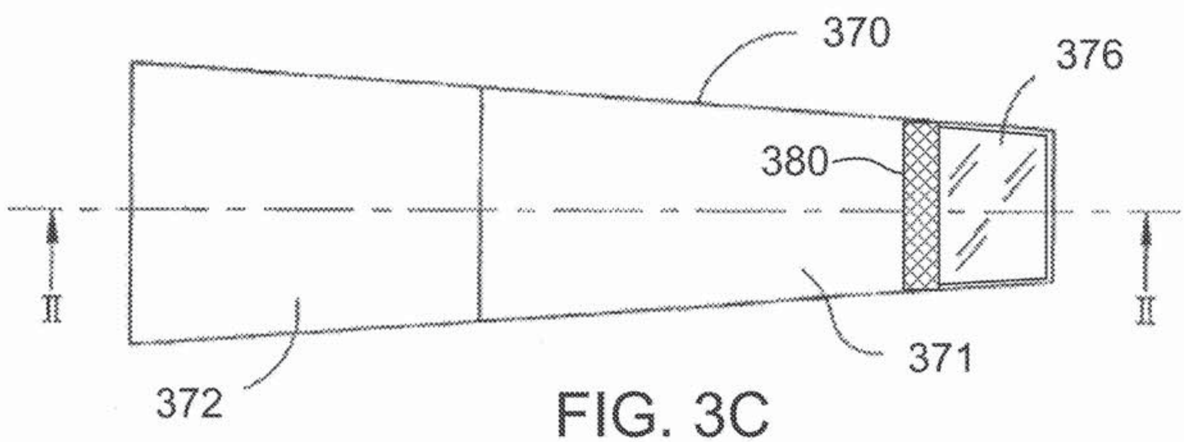


FIG. 3C

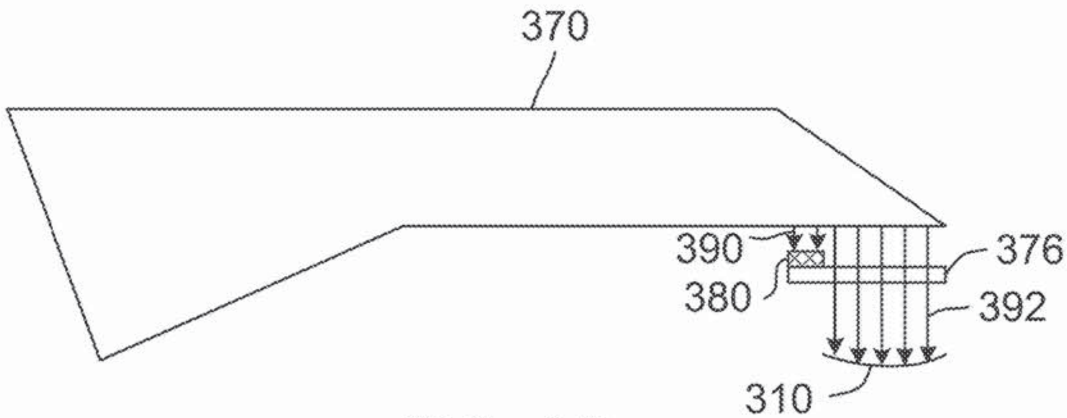


FIG. 3D

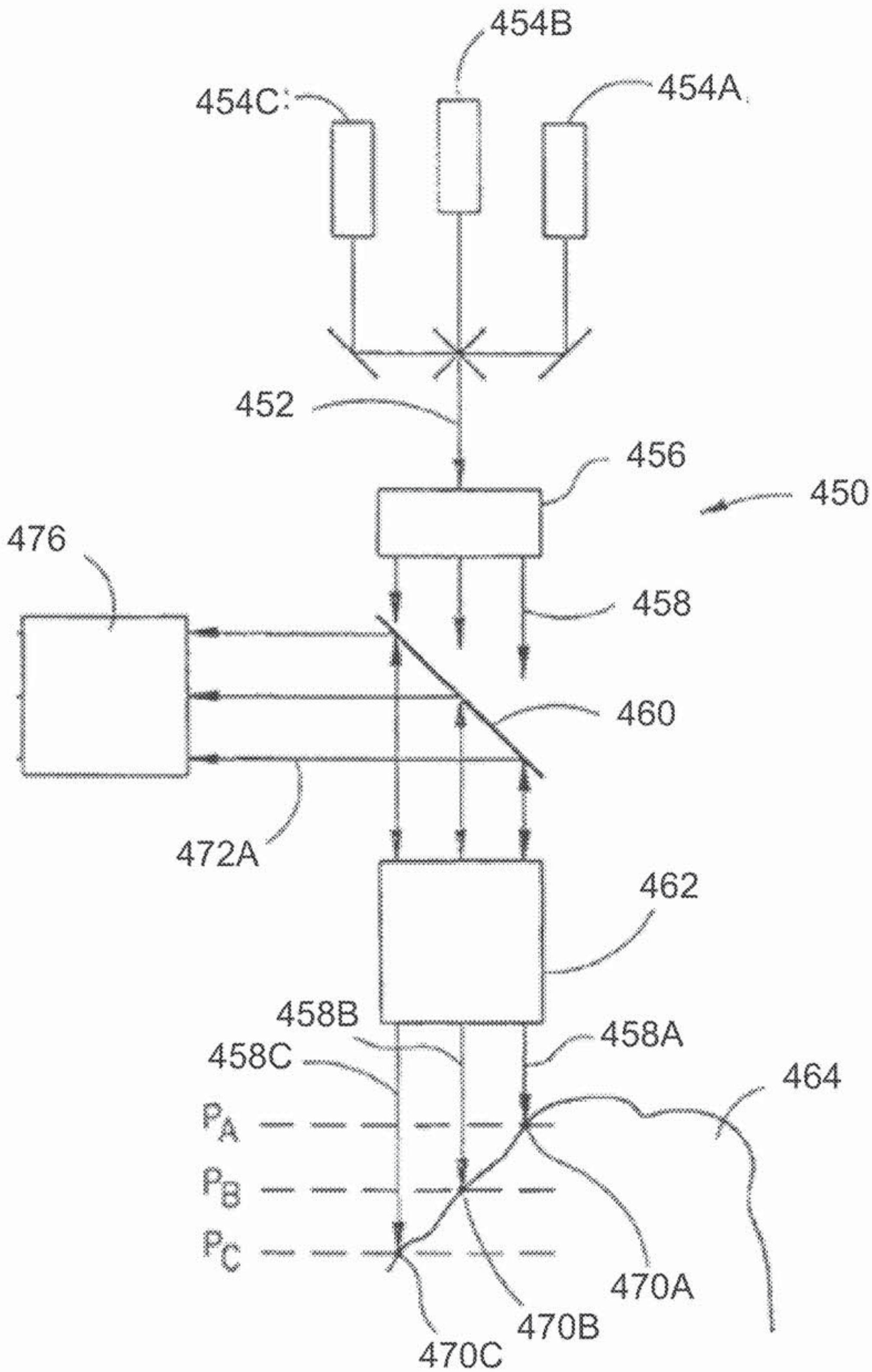

454B
454C
454A
452
456
450
476
458
460
472A
462
458B
458C
458A
464
P_A
P_B
P_C
470A
470B
470C

FIG. 4

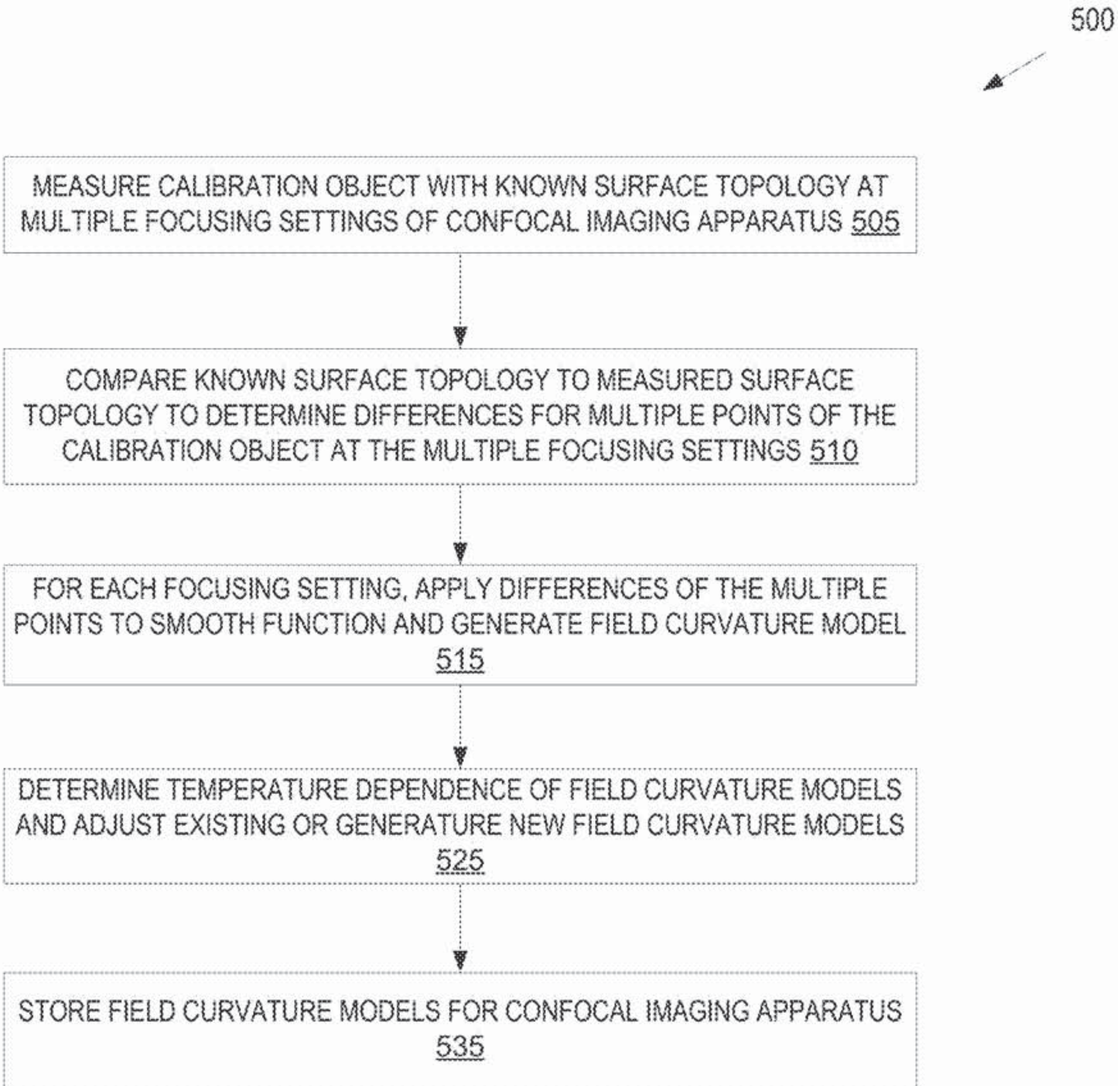

500
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 505
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 510
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SMOOTH FUNCTION AND GENERATE FIELD CURVATURE MODEL 515
DETERMINE TEMPERATURE DEPENDENCE OF FIELD CURVATURE MODELS AND ADJUST EXISTING OR GENERATURE NEW FIELD CURVATURE MODELS 525
STORE FIELD CURVATURE MODELS FOR CONFOCAL IMAGING APPARATUS 535

FIG. 5A

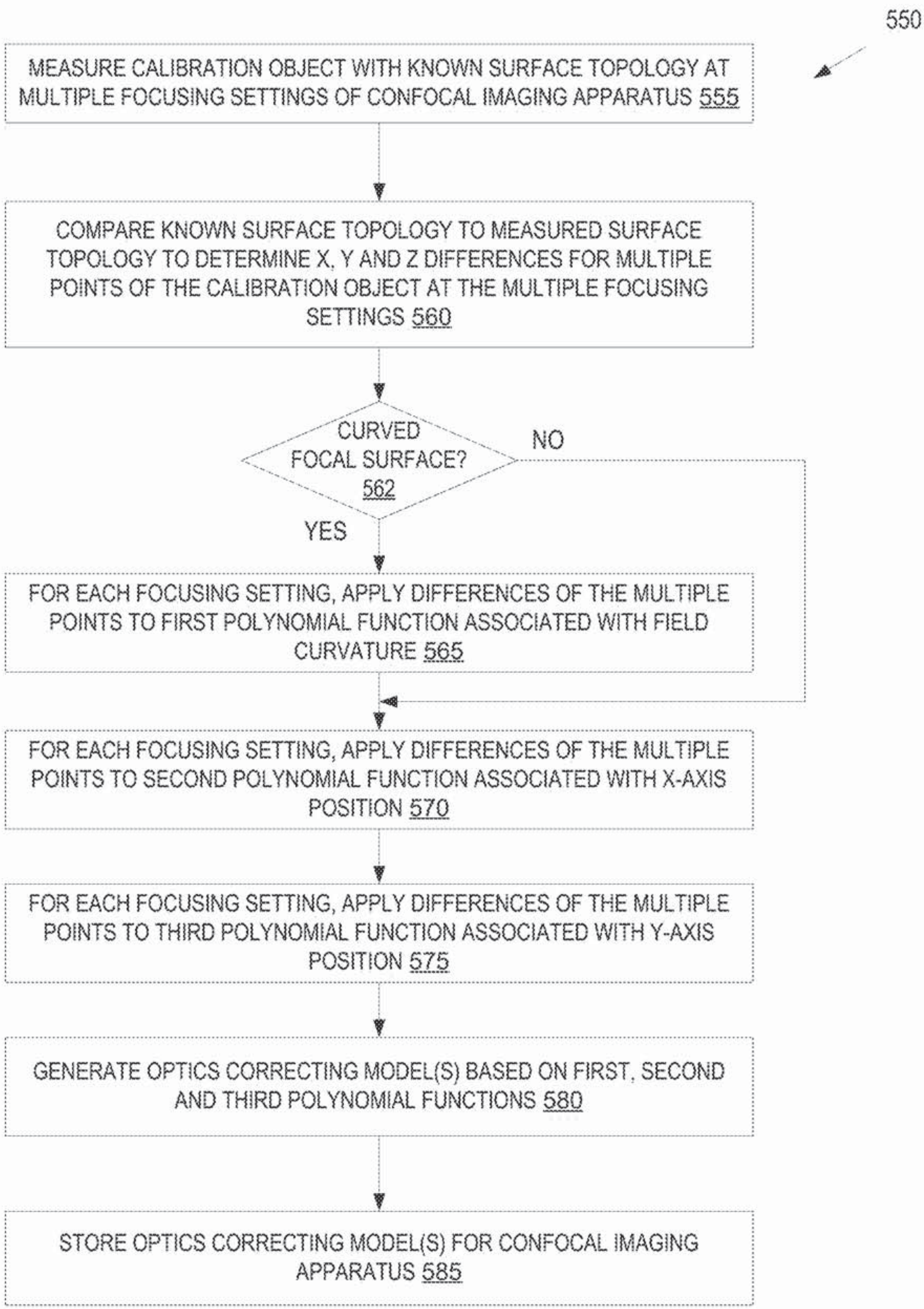

550
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 555
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE X, Y AND Z DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 560
CURVED FOCAL SURFACE? 562
NO
YES
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO FIRST POLYNOMIAL FUNCTION ASSOCIATED WITH FIELD CURVATURE 565
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SECOND POLYNOMIAL FUNCTION ASSOCIATED WITH X-AXIS POSITION 570
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO THIRD POLYNOMIAL FUNCTION ASSOCIATED WITH Y-AXIS POSITION 575
GENERATE OPTICS CORRECTING MODEL(S) BASED ON FIRST, SECOND AND THIRD POLYNOMIAL FUNCTIONS 580
STORE OPTICS CORRECTING MODEL(S) FOR CONFOCAL IMAGING APPARATUS 585

FIG. 5B

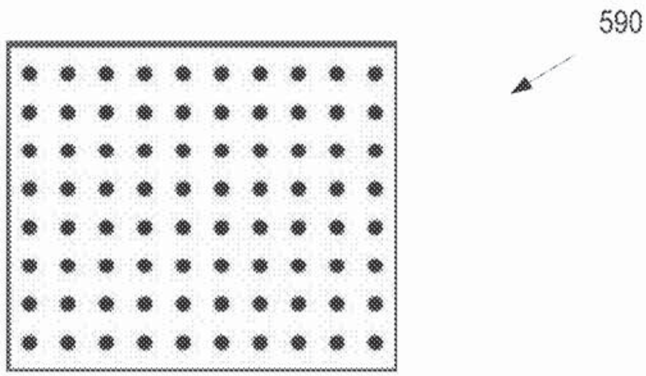


FIG. 5C

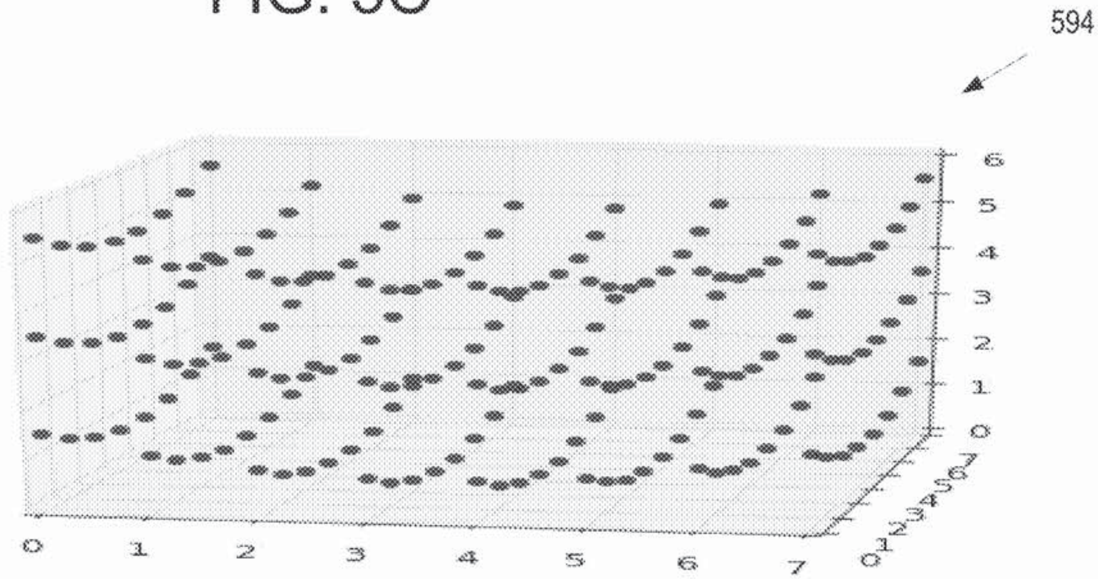


FIG. 5D

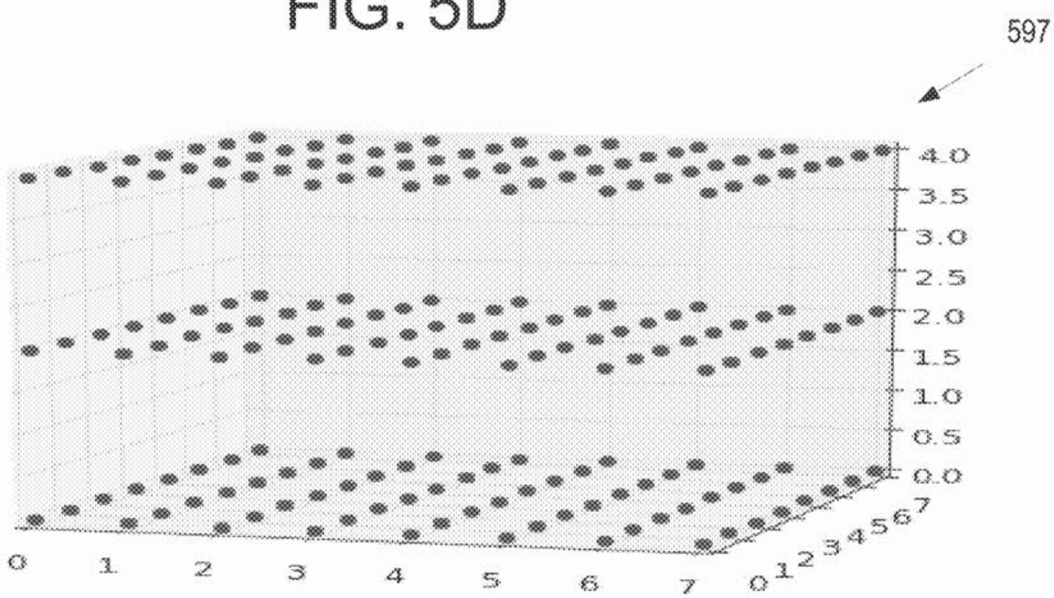


FIG. 5E

600

RECEIVE INTENSITY MEASUREMENTS GENERATED BY PIXELS OF A DETECTOR OF A CONFOCAL IMAGING APPARATUS, WHEREIN EACH PIXEL PROVIDES INTENSITY MEASUREMENTS FOR AN ASSOCIATED RETURNING LIGHT BEAM FROM AN ARRAY OF RETURNING LIGHT BEAMS THAT HAVE BEEN REFLECTED OFF OF AN IMAGED THREE DIMENSIONAL SURFACE, AND WHEREIN EACH RETURNING LIGHT BEAM OF THE ARRAY OF RETURNING LIGHT BEAMS IS ASSOCIATED WITH A POINT OF THE THREE DIMENSIONAL OBJECT 610

DETERMINE, FOR EACH PIXEL, A FOCUSING SETTING OF THE CONFOCAL IMAGING APPARATUS THAT PROVIDES A MAXIMUM MEASURED INTENSITY 620

DETERMINE, FOR EACH PIXEL, A DEPTH OF A POINT OF THE THREE DIMENSIONAL OBJECT ASSOCIATED WITH THE PIXEL THAT CORRESPONDS TO THE DETERMINED FOCUSING SETTING 630

ADJUST THE DEPTH OF POINTS OF THE THREE DIMENSIONAL OBJECT BASED ON APPLYING THE DETERMINED FOCUSING SETTING FOR THE PIXELS ASSOCIATED WITH THE POINTS TO A FIELD CURVATURE MODEL TO COMPENSATE FOR A NON-FLAT FOCUSING SURFACE OF THE CONFOCAL IMAGING APPARATUS 640

DETERMINE A SHAPE OF THE THREE DIMENSIONAL OBJECT BASED AT LEAST IN PART ON THE ADJUSTED DEPTH 650

FIG. 6

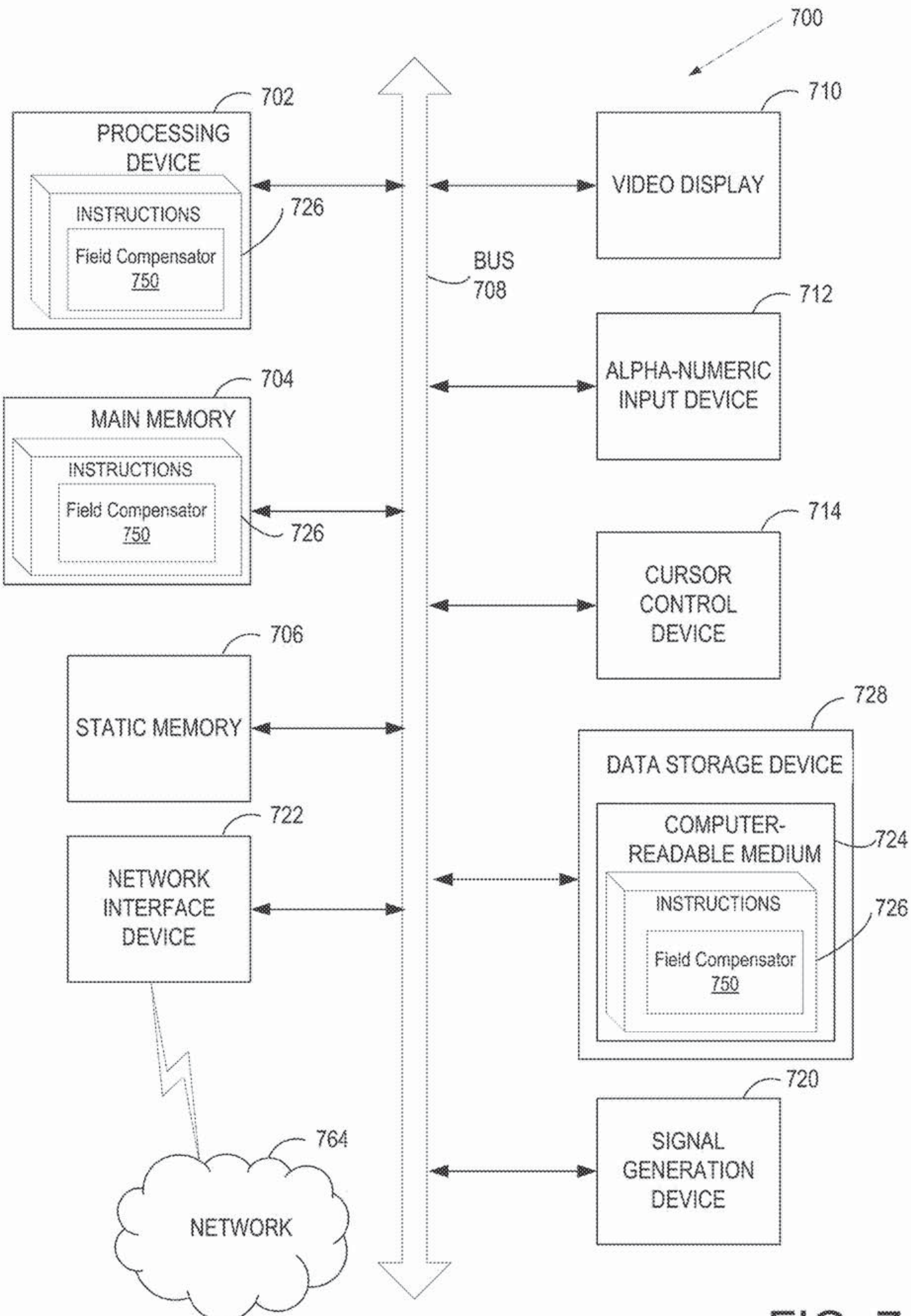

700
702
PROCESSING DEVICE
INSTRUCTIONS
Field Compensator 750
726
704
MAIN MEMORY
INSTRUCTIONS
Field Compensator 750
726
706
STATIC MEMORY
722
NETWORK INTERFACE DEVICE
764
NETWORK
BUS 708
710
VIDEO DISPLAY
712
ALPHA-NUMERIC INPUT DEVICE
714
CURSOR CONTROL DEVICE
728
DATA STORAGE DEVICE
COMPUTER-READABLE MEDIUM
724
INSTRUCTIONS
Field Compensator 750
726
720
SIGNAL GENERATION DEVICE

FIG. 7

IMAGING APPARATUS WITH SIMPLIFIED OPTICAL DESIGN

RELATED APPLICATIONS

This patent application is a continuation application of U.S. patent application Ser. No. 15/610,515, filed May 31, 2017, which is a divisional application of U.S. patent application Ser. No. 14/825,173, filed Aug. 13, 2015, which claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application No. 62/037,778, filed Aug. 15, 2014, all of which are herein incorporated by reference.

TECHNICAL FIELD

Embodiments of the present invention relate to the field of imaging and, in particular, to a system and method for performing confocal imaging of a three dimensional surface.

BACKGROUND

A great variety of methods and systems have been developed for direct optical measurement of teeth and the subsequent automatic manufacture of dentures. The term "direct optical measurement" signifies surveying of teeth in the oral cavity of a patient. This facilitates the obtainment of digital constructional data necessary for the computer-assisted design (CAD) or computer-assisted manufacture (CAM) of tooth replacements without having to make any cast impressions of the teeth. Such systems typically include an optical probe coupled to an optical pick-up or receiver such as charge coupled device (CCD) or complementary meta-oxide semiconductor (CMOS) sensor and a processor implementing a suitable image processing technique to design and fabricate virtually the desired product.

One type of system that performs intra-oral scans is a system that uses confocal imaging to image a three dimensional surface. Such systems that use confocal imaging typically include field lenses to flatten an imaging field and enable flat focal planes for emitted light beams. Such flat focal planes ensure that the surface topology of scanned three dimensional surfaces is accurate. However, the field lenses are diverging lenses that open the rays of the light beams. This causes the optics of the confocal imaging apparatus to be enlarged. Additionally, the field lenses should be aligned to ensure accuracy. Such alignment can be a time consuming and challenging process.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

FIG. 1A illustrates a functional block diagram of a confocal imaging apparatus according to one embodiment.

FIG. 1B illustrates a block diagram of a computing device that connects to a confocal imaging apparatus, in accordance with one embodiment.

FIG. 2A illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment.

FIG. 2B illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with another embodiment.

FIG. 2C illustrates optics of a confocal imaging apparatus with a field lens for which changes in a focusing setting cause changes in magnification, in accordance with another embodiment.

FIG. 3A is a top view of a probing member of a confocal imaging apparatus that includes a prism, in accordance with an embodiment of the invention.

FIG. 3B is a longitudinal cross-section through line II-II of the probing member in FIG. 3A.

FIG. 3C is a view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. 3D is a side view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. 4 is a schematic illustration of optics of a confocal imaging apparatus, in accordance with one embodiment.

FIG. 5A is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface.

FIG. 5B is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification.

FIG. 5C illustrates one example calibration object, in accordance with one embodiment.

FIG. 5D illustrates a chart showing a distribution of points of a calibration object as measured by a confocal imaging apparatus, in accordance with one embodiment.

FIG. 5E illustrates a chart showing a distribution of points in a world coordinate system, in accordance with one embodiment.

FIG. 6 is a flow chart showing one embodiment of a method for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model calibrated to a confocal imaging apparatus.

FIG. 7 illustrates a block diagram of an example computing device, in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

Described herein is a confocal imaging apparatus having a non-flat focal surface. The non-flat focal surface may be caused by the optics of the confocal imaging apparatus lacking a field lens. As is discussed in greater detail below, the lack of a field lens in the confocal imaging apparatus introduces challenges but also provides numerous advantages. For example, a confocal imaging apparatus without a field lens is smaller, lighter and easier to manufacture than a confocal imaging apparatus having a field lens. Embodiments discussed herein show how to overcome the challenges in designing and using a confocal imaging apparatus lacking a field lens.

Also described herein is a large field confocal imaging apparatus having focusing optics that change a magnification of a focal surface with changes in a focusing setting. As is discussed in greater detail below, the change in magnification introduces challenges that are overcome in embodiments.

In one embodiment, a confocal imaging apparatus includes an illumination module to generate an array of light beams. Focusing optics of the confocal imaging apparatus perform confocal focusing of an array of light beams onto a non-flat focal surface and direct the array of light beams toward a three dimensional object to be imaged. A translation mechanism of the confocal imaging apparatus adjusts a location of at least one lens to displace the non-flat focal surface along an imaging axis. A detector of the confocal imaging apparatus measures intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics. Intensities of the array of returning light beams are measured for

locations of the at least one lens for determination of positions on the imaging axis of points of the three dimensional object. Detected positions of one or more points are adjusted to compensate for the non-flat focal surface. Thus, an object may be accurately imaged despite the non-flat focal surface of the confocal imaging apparatus.

FIG. **1**A illustrates a functional block diagram of a confocal imaging apparatus **20** according to one embodiment. FIG. **1**B illustrates a block diagram of a computing device **24** that connects to the confocal imaging apparatus **20**. Together, the confocal imaging apparatus **20** and computing device **24** may form a system for generating three dimensional images of scanned objects. The computing device **24** may be connected to the confocal imaging apparatus **20** directly or indirectly and via a wired or wireless connection. For example, the confocal imaging apparatus **20** may include a network interface controller (NIC) capable of communicating via Wi-Fi, via third generation (3G) or fourth generation (4G) telecommunications protocols (e.g., global system for mobile communications (GSM), long term evolution (LTE), Wi-Max, code division multiple access (CDMA), etc.), via Bluetooth, via Zigbee, or via other wireless protocols. Alternatively, or additionally, confocal imaging apparatus may include an Ethernet network interface controller (NIC), a universal serial bus (USB) port, or other wired port. The NIC or port may connect the confocal imaging apparatus to the computing device via a local area network (LAN). Alternatively, the confocal imaging apparatus **20** may connect to a wide area network (WAN) such as the Internet, and may connect to the computing device **24** via the WAN. In an alternative embodiment, confocal imaging apparatus **20** is connected directly to the computing device (e.g., via a direct wired or wireless connection). In one embodiment, the computing device **24** is a component of the confocal imaging apparatus **20**.

Referring now to FIG. **1**A, in one embodiment confocal imaging apparatus **20** includes a semiconductor laser unit **28** that emits a focused light beam, as represented by arrow **30**. The light beam **30** passes through a polarizer **32**. Polarizer **32** polarizes the light beam passing through polarizer **32**. Alternatively, polarizer **32** may be omitted in some embodiments. The light beam then enters into an optic expander **34** that improves a numerical aperture of the light beam **30**. The light beam **30** then passes through an illumination module **38**, which splits the light beam **30** into an array of incident light beams **36**, represented here, for ease of illustration, by a single line. The illumination module **38** may be, for example, a grating or a micro lens array that splits the light beam **30** into an array of light beams **36**. In one embodiment, the array of light beams **36** is an array of telecentric light beams. Alternatively, the array of light beams may not be telecentric.

The confocal imaging apparatus **20** further includes a unidirectional mirror or beam splitter (e.g., a polarizing beam splitter) **40** that passes the array of light beams **36**. A unidirectional mirror **40** allows transfer of light from the semiconductor laser **28** through to downstream optics, but reflects light travelling in the opposite direction. A polarizing beam splitter allows transfer of light beams having a particular polarization and reflects light beams having a different (e.g., opposite) polarization. In one embodiment, the unidirectional mirror or beam splitter **40** has a small central aperture. The small central aperture may improve a measurement accuracy of the confocal imaging apparatus **20**. In one embodiment, as a result of a structure of the unidirectional mirror or beam splitter **40**, the array of light beams will yield a light annulus on an illuminated area of an imaged object as long as the area is not in focus. Moreover, the annulus will become a completely illuminated spot once in focus. This ensures that a difference between measured intensities of out-of focus points and in-focus points will be larger.

Along an optical path of the array of light beams after the unidirectional mirror or beam splitter **40** are confocal focusing optics **42**, and an endoscopic probing member **46**. Additionally, a quarter wave plate may be disposed along the optical path after the unidirectional mirror or beam splitter **40** to introduce a certain polarization to the array of light beams. In some embodiments this may ensure that reflected light beams will not be passed through the unidirectional mirror or beam splitter **40**. Confocal focusing optics **42** may additionally include relay optics (not shown). Confocal focusing optics **42** may or may not maintain the same magnification of an image over a wide range of distances in the Z direction, wherein the Z direction is a direction of beam propagation (e.g., the Z direction corresponds to an imaging axis that is aligned with an optical path of the array of light beams **36**). The relay optics enable the confocal imaging apparatus **20** to maintain a certain numerical aperture for propagation of the array of light beams **36**. The confocal focusing optics **42** and endoscopic probing member **46** are discussed in greater detail with reference to FIGS. **2**A-**2**C.

The endoscopic probing member **46** may include a rigid, light-transmitting medium, which may be a hollow object defining within it a light transmission path or an object made of a light transmitting material, e.g. a glass body or tube. In one embodiment, the endoscopic probing member **46** include a prism such as a folding prism. At its end, the endoscopic probing member **46** may include a mirror of the kind ensuring a total internal reflection. Thus, the mirror may direct the array of light beams towards a teeth segment **26** or other object. The endoscope probing member **46** thus emits array of light beams **48**, which impinge on to surfaces of the teeth section **26**.

The array of light beams **48** are arranged in an X-Y plane, in the Cartesian frame **50**, propagating along the Z axis. As the surface on which the incident light beams hits is an uneven surface, illuminated spots **52** are displaced from one another along the Z axis, at different (X_i, Y_i) locations. Thus, while a spot at one location may be in focus of the confocal focusing optics **42**, spots at other locations may be out-of-focus. Therefore, the light intensity of returned light beams of the focused spots will be at its peak, while the light intensity at other spots will be off peak. Thus, for each illuminated spot, multiple measurements of light intensity are made at different positions along the Z-axis. For each of such (X_i, Y_i) location, the derivative of the intensity over distance (Z) may be made, with the Z_i yielding maximum derivative, Z_0, being the in-focus distance. As pointed out above, the incident light from the array of light beams **48** forms a light disk on the surface when out of focus and a complete light spot when in focus. Thus, the distance derivative will be larger when approaching in-focus position, increasing accuracy of the measurement.

The light scattered from each of the light spots includes a beam travelling initially in the Z axis along the opposite direction of the optical path traveled by the array of light beams **48**. Each returned light beam in an array of returning light beams **54** corresponds to one of the incident light beams in array of light beams **36**. Given the asymmetrical properties of unidirectional mirror or beam splitter **40**, the returned light beams are reflected in the direction of detection optics **60**.

The detection optics **60** may include a polarizer **62** that has a plane of preferred polarization oriented normal to the plane polarization of polarizer **32**. Alternatively, polarizer **32** and polarizer **62** may be omitted in some embodiments. The array of returning light beams **54** may pass through imaging optics **64** in one embodiment. The imaging optics **64** may be one or more lenses. Alternatively, the detection optics **60** may not include imaging optics **64**. In one embodiment, the array of returning light beams **54** further passes through a matrix **66**, which may be an array of pinholes. Alternatively, no matrix **66** is used in some embodiments. The array of returning light beams **54** are then directed onto a detector **68**.

The detector **68** is an image sensor having a matrix of sensing elements each representing a pixel of the image. If matrix **66** is used, then each pixel further corresponds to one pinhole of matrix **66**. In one embodiment, the detector is a charge coupled device (CCD) sensor. In one embodiment, the detector is a complementary metal-oxide semiconductor (CMOS) type image sensor. Other types of image sensors may also be used for detector **68**. The detector **68** detects light intensity at each pixel.

In one embodiment, detector **68** provides data to computing device **24**. Thus, each light intensity measured in each of the sensing elements of the detector **68**, is then captured and analyzed, in a manner to be described below, by processor **24**.

Confocal imaging apparatus **20** further includes a control module **70** connected both to semiconductor laser **28** and a motor **72**, voice coil or other translation mechanism. In one embodiment, control module **70** is or includes a field programmable gate array (FPGA) configured to perform control operations. Motor **72** is linked to confocal focusing optics **42** for changing a focusing setting of confocal focusing optics **42**. This may adjust the relative location of an imaginary non-flat focal surface of confocal focusing optics **42** along the Z-axis (e.g., in the imaging axis). Control module **70** may induce motor **72** to axially displace (change a location of) one or more lenses of the confocal focusing optics **42** to change the focal depth of the imaginary non-flat focal surface. In one embodiment, motor **72** or confocal imaging apparatus **20** includes an encoder (not shown) that accurately measures a position of one or more lenses of the confocal focusing optics **42**. The encoder may include a sensor paired to a scale that encodes a linear position. The encoder may output a linear position of the one or more lenses of the confocal focusing optics **42**. The encoder may be an optical encoder, a magnetic encoder, an inductive encoder, a capacitive encoder, an eddy current encoder, and so on. After receipt of feedback that the location of the one or more lenses has changed, control module **70** may induce laser **28** to generate a light pulse. Control unit **70** may additionally synchronize image-capturing module **80** from FIG. **1**B to receive and/or store data representative of the light intensity from each of the sensing elements at the particular location of the one or more lenses (and thus of the focal depth of the imaginary non-flat focal surface). In subsequent sequences, the location of the one or more lenses (and thus the focal depth) will change in the same manner and the data capturing will continue over a wide focal range of confocal focusing optics **42**.

Referring now to FIG. **1**B, image capturing module **80** may capture images responsive to receiving image capture commands from the control unit **70**. The captured images may be associated with a particular focusing setting (e.g., a particular location of one or more lenses in the confocal focusing optics as output by the encoder). Image processing module **82** then processes captured images captured over multiple different focusing settings. Image processing module **82** includes a depth determiner **90** and a field compensator **92** for processing image data.

Depth determiner **90** determines the relative intensity in each pixel over the entire range of focal settings of confocal focusing optics **42** from received image data. Once a certain light spot associated with a particular pixel is in focus, the measured intensity will be maximal for that pixel. Thus, by determining the corresponding to the maximal light intensity or by determining the maximum displacement derivative of the light intensity, for each pixel, the relative position of each light spot along the Z axis can be determined for each pixel. Thus, data representative of the three-dimensional pattern of a surface in the teeth segment **26** or other three dimensional object can be obtained.

In embodiments, the confocal focusing optics **42** of confocal imaging apparatus **20** lack field lenses. The purpose of the field lens is to flatten a focal field and thus produce a flat focal plane for the array of light beams. For confocal imaging apparatuses with field lenses, each light beam from the array of light beams focuses on the same flat focal plane. However, without such field lenses the array of light beams focus on an imaginary non-flat focal surface (e.g., on a curved focal surface). This causes the Z axis information that depth determiner **90** computes to be distorted for many pixels.

Field compensator **92** compensates for the curved field caused by the lack of a field lens. Field compensator **92** may also compensate for changes in a position of the curved focal surface caused by temperature and/or for magnification changes caused by changes in a focusing setting. Field compensator **92** applies a field curvature model **94** and/or other optics compensation model (not shown) to each Z axis measurement of each pixel to correct for field curvature, temperature and/or magnification changes. In one embodiment, a different field curvature model **94** (or other optics compensation model) is applied for each focusing setting of the confocal imaging apparatus **20**. This is because the amount of field curvature and/or magnification may change with changes in the focusing setting. Alternatively, a single field curvature model **94** (or other optics compensation model) may account for the changes in the field curvature caused by changes in the focusing setting and/or for changes in magnification caused by changes in the focusing setting. For each combination of an X,Y pixel location and a focusing setting (e.g., a z-axis position of one or more lenses of the focusing optics), a particular depth adjustment may be applied based on the field curvature model or models. Additionally, an X location adjustment and/or a Y location adjustment bay be applied based on the field curvature model and/or other optics compensation model. In one embodiment, for each combination of an X,Y pixel location, a focusing setting, and a temperature reading or a z-axis position of a measured element whose position changes with changes in temperature, a particular depth adjustment may be applied based on the field curvature model or models. The adjusted depth (z-axis) values represent the actual z-axis values of the imaged surface.

A three-dimensional representation may be constructed based on the corrected measurement data and displayed via a user interface **84**. The user interface **84** may be a graphical user interface that includes controls for manipulating a display of the three-dimensional representation (e.g., viewing from different angles, zooming-in or out, etc.). In addition, data representative of the surface topology of the scanned object may be transmitted to remote devices by a

communication module **88** for further processing or use (e.g., to generate a three dimensional virtual model of the scanned object).

By capturing, in this manner, an image from two or more angular locations around the structure, e.g. in the case of a teeth segment from the buccal direction, from the lingual direction and optionally from above the teeth, an accurate three-dimensional representation of the teeth segment may be reconstructed. This may allow a virtual reconstruction of the three-dimensional structure in a computerized environment or a physical reconstruction in a CAD/CAM apparatus. For example, a particular application is imaging of a segment of teeth having at least one missing tooth or a portion of a tooth. In such an instance, the image can then be used for the design and subsequent manufacture of a crown or any other prosthesis to be fitted into this teeth segment.

FIG. **2**A illustrates optics **200** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **200** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**.

The optics **200** include an illumination module **38**, a unidirectional mirror or beam splitter **40**, a series of lenses that may correspond to confocal focusing optics **42**, and folding prism **220** arranged along an optical path traversed by an array of light beams **225**. The optical path is shown to be a linear path. However, in embodiments one or more of the components of optics **200** may change a direction of the optical path. For example, the folding prism **220** may include a mirror (not shown) that may reflect light beams at an angle. An example of such a folding prism is shown in FIG. **3**B. Referring back to FIG. **2**, an imaging axis **240** is shown that is aligned to the optical path traversed by the array of light beams **225**. The imaging axis **240** is a Z-axis that represents depth. As used herein, the imaging axis (or Z axis) may be a curvilinear coordinate axis that corresponds to the optical path. Thus, if the optical path changes direction, the imaging axis changes direction correspondingly.

Illumination module **38** is a source of multiple light beams. In one embodiment, illumination module is a micro lens array that divides an incoming light beam into array of light beams **225**. In one embodiment, the array of light beams output by the illumination module **38** is an array of telecentric light beams. Accordingly, chief rays of the array of light beams may be parallel to each other. Unidirectional mirror or beam splitter **40** is disposed along the optical path of the array of light beams, and passes the array of light beams received from the unidirectional mirror or beam splitter **40**.

In one embodiment, the confocal focusing optics are divided into a series of lens groups including a first lens group **205**, a second lens group **215** and a third lens group **210**. First and/or second lens groups **205**, **215** may act as relay optics. The first and second lens groups **205**, **215** are configured to focus the array of light beams and compensate for optical aberrations. Optical aberrations that may be corrected include shape aberrations, coma, stigmatism, and so forth. In one embodiment, the first and second lens groups **205**, **215** are configured to produce an approximately rectangular field having minimal optical distortion. The first lens group **205** and second lens group **215** may have a fixed position relative to each other and to other components of the optics **200**. The third lens group **210** has a variable location that may be adjusted to change a location of a curved focal surface produced by the optics **200**.

The third lens group **210** is movable along the imaging axis (z axis), but has a fixed position normal to the imaging axis. A focusing setting of the focusing optics can be adjusted by moving the third lens group **210** along the imaging axis. Third lens group **210** may be adjusted to perform scanning of an object. To scan an object, the third lens group **210** may be displaced to numerous different locations (encoder positions) along the imaging axis **240**, and images may be taken at each location. In one embodiment, an axial gain of the focusing optics is approximately 7×. Accordingly, a displacement of the third lens group **210** adjusts a location of a curved focal surface **230** by seven times the amount of displacement. For example, a 1 mm displacement of the third lens group **210** causes a position of the curved focal surface (also referred to as a curved focal plane) by 7 mm. This enables the optics **200** to be compact and minimizes movement during operation.

In one embodiment, second lens group **215** focuses the array of light beams **225** into prism **220**, which may be a folding prism. Prism **220** may be configured to provide an appropriate refractive index (e.g., that corresponds to a refractive index of glass).

The optics **200** lack any field lens. A field lens is used to flatten a focal surface (flatten an imaging field) to achieve a flat focal plane. As shown, there is no field lens between the illumination module **38** and the unidirectional mirror or beam splitter **40**. Nor is there a field lens near prism **220** or a field lens between the unidirectional mirror or beam splitter **40** and a detector (not shown). The lack of a field lens introduces numerous advantages over confocal imaging apparatuses that use field lenses. The field lens is a diverging lens that causes a radius of the lenses used for the focusing optics and/or for relay optics to be larger. This in turn increases the amount of material (e.g., glass) used in the lenses and thus increases a weight of the confocal imaging apparatus. Additionally, the larger lenses cause a thickness of the confocal imaging apparatus to be larger. For example, an example confocal imaging apparatus with a field lens includes a largest lens having a distance from an optical axis to an outer perimeter of the lens of about 15 mm. In contrast, the same confocal imaging apparatus without a field lens may include a largest lens having a distance from the optical axis to an outer perimeter of the lens of less than 15 mm (e.g., less than 13 mm or about 9 mm in embodiments).

In a confocal imaging apparatus having a field lens, the field lens may be positioned between the illumination module **38** and the unidirectional mirror or beam splitter **40**. This causes a spacing between the illumination module **38** and the unidirectional mirror or beam splitter **40** to be about 7 mm. Additionally, a corresponding field lens would be placed between the unidirectional mirror or beam splitter **40** and a detector (not shown) at a distance of about 7 mm. In contrast, by eliminating the field lens, the distance **235** between the illumination module **38** and the unidirectional mirror or beam splitter **40** may be less than 7 mm (e.g., less than 5 mm or about 2 mm in embodiments). This further reduces the size of the confocal imaging apparatus.

As mentioned, if a field lens is used in a confocal imaging apparatus, then in actuality two field lenses are used. These two field lenses should be matching field lenses and should be carefully aligned to one another. This alignment can be a time consuming process. Additionally, failure to exactly align these field lenses introduces inaccuracy into the confocal imaging apparatus. Accordingly, an accuracy of the confocal imaging apparatus can be improved and an ease of manufacture for the confocal imaging apparatus can be improved by eliminating the field lens.

The lack of a field lens causes the focal surface **230** to be a curved focal surface (or other non-flat focal surface). The

shape of the curved focal surface **230** may depend on the focusing setting of the focusing optics (e.g., the location of the third lens group **210**). The curved focal surface may introduce significant error into the confocal imaging apparatus, which accounts for the inclusion of field lenses in prior confocal imaging apparatuses. However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the lack of a field lens.

As shown, the confocal focusing optics is a non-telecentric optical system. Accordingly, magnification of an imaged object may change with changes in depth and/or in changes of focal settings. However, such magnification changes (and any accompanying distortion) may be accommodated and corrected by the field compensator based on application of a field curvature model. Alternatively, the confocal focusing optics may operate in a telecentric mode, and distance-introduced magnification changes may be avoided.

FIG. **2**B illustrates optics **250** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **250** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200**, optics **250** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. The series of lens groups include a first lens group **255** with a fixed position and a second lens group **265** that is movable along an imaging axis **280** corresponding to a direction of propagation for an array of light beams **270**.

The array of light beams **270** are focused onto a curved focal surface **275**. Though the optics **250** are not telecentric, magnification is preserved (fixed) with changes in focusing settings because the array of light beams are collimated between first lens group **255** and second lens group **265**. For optics **250**, axial gain is 1×. Accordingly, a displacement of 1 mm of the second lens group **265** causes a displacement of the curved focal surface of 1 mm.

An object may be placed along the beam path to be imaged. The array of light beams **285** reflect off of the object and an array of returning light beams return back through the series of lens groups. The array of returning light beams **285** is then reflected by the unidirectional mirror (or beam splitter) **40** onto detector **68**. As shown, the optics **250** lack a field lens between the unidirectional mirror or beam splitter **40** and the illumination module **38** and further lack a field lens between the unidirectional mirror or beam splitter **40** and the detector **68**. Accordingly, the focal surface for the optics **250** is a curved focal surface **275**.

Embodiments have been discussed herein with reference to a confocal imaging apparatus that lacks a field lens and that has a curved focal surface. However, in some embodiments the confocal imaging apparatus includes one or more field lenses and thus has a flat focal surface. For such embodiments, the confocal imaging apparatus operates in a non-telecentric mode, and magnification at a focal plane changes with changes in focusing settings of the confocal imaging apparatus.

FIG. **2**C illustrates one example of optics **285** for a confocal imaging apparatus that includes a field lens, in accordance with one embodiment. The optics **285** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200** and optics **250**, optics **285** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. However, optics **285** also include a field lens **288** that causes a flat focal plane **299**. The series of lens groups include a first lens group **290** with a fixed position, a second lens group **292** with a fixed position and a third lens group **294** that is movable along an imaging axis **297** corresponding to a direction of propagation for an array of light beams **298**.

The array of light beams **298** are focused onto flat focal plane **299**. Magnification at the flat foal plane **299** changes with changes in focusing settings. The changes in magnification may introduce significant error into the confocal imaging apparatus. Accordingly, the focusing optics for some large field confocal imaging apparatuses maintain the same magnification with changes in focusing settings (e.g., with changes in a position of one or more lenses along an imaging axis). However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the change in magnification.

FIGS. **3**A-**3**B illustrate a probing member **300** in accordance with one embodiment. The probing member **300** is made of a light transmissive material such as glass. In one embodiment, the probing member **300** acts as a prism and corresponds to prism **220** of FIG. **2**. Probing member **300** may include an anterior segment **301** and a posterior segment **302**, tightly bonded (e.g., glued) in an optically transmissive manner at **303**. Probing member **300** may additionally include a slanted face **304** covered by a reflective mirror layer **305**. A window **306** defining a sensing surface **307** may be disposed at a bottom end of the anterior segment **301** in a manner leaving an air gap **308**. The window **306** may be fixed in position by a holding structure which is not shown. An array of light rays or beams **309** are represented schematically. As can be seen, the array of light beams **309** are reflected at the walls of the probing member at an angle in which the walls are totally reflective and finally reflect on mirror layer **305** out through the sensing face **307**. The array of light beams **309** focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure).

Various components of the confocal imaging apparatus may dissipate considerable amounts of heat relative to a size of the confocal imaging apparatus. For example, the confocal imaging apparatus may include a CMOS sensor and an FPGA, both of which may produce heat. Accordingly, internal temperatures of the confocal imaging apparatus may rise over time during use. At any given time, different portions of the confocal imaging apparatus may have different temperatures. A temperature distribution within the confocal imaging apparatus is referred to as a thermal state of the confocal imaging apparatus. The thermal state of the confocal imaging apparatus may affect various optical parameters. For example, the thermal state may cause the positions of one or more optical components to move within the confocal imaging apparatus due to expansion of the various components in accordance with thermal expansion coefficients of these components. Additionally, the refractive coefficient of one or more lens of the confocal imaging apparatus may change with changes in the thermal state. Such changes cause measurements produced by the confocal imaging apparatus to change with changes in the internal thermal state. Some regions of the confocal imaging apparatus are more sensitive to thermal change than others (e.g., due to a high optical gain). For example, some optical elements may have an axial gain of up to about 7.5 in an embodiment. For such optical elements, a 10 μm movement due to changes in the thermal state could cause up to a 75 μm shift in a measurement. Accordingly, in some embodiments, as shown in FIGS. **3**C-**3**D, an internal target is used to adjust for measurement changes caused by changes in the thermal

state. Alternatively, multiple temperature sensors may be disposed within the confocal imaging apparatus and used to determine changes in the thermal state.

FIGS. **3C-3D** illustrate a probing member **370** that includes an internal target **380**, in accordance with one embodiment. The probing member **370** is substantially similar to probing member **300**. For example, probing member **370** may be made of a light transmissive material such as glass, and may act as a prism. Probing member **370** may include an anterior segment **371** and a posterior segment **372**, tightly bonded (e.g., glued) in an optically transmissive manner. Probing member **370** may additionally include a slanted face covered by a reflective mirror layer. A window **376** defining a sensing surface may be disposed at a bottom end of the anterior segment **371**. The window **376** may be glass or another transparent material, and may be fixed in position by a holding structure which is not shown.

Probing member **370** additionally includes internal target **380** secured to the anterior segment **371** of the probing member **370** within a field of view (FOV) of the probing member **370**. The internal target **380** may be a rigid reflective material that will reflect light beams. The internal target **380** may be secured at a fixed position within the probing member **300**. Since the internal target **380** is a part of the probing member **370**, the location of the internal target **380** should remain constant. In one embodiment, the internal target **380** takes up approximately 500 μm to 1 mm of the FOV.

During measurement, an array of light rays or beams **390-392** is projected out of the anterior segment **371**. As can be seen, the internal target **380** is in the path of light beams **390**. Accordingly, the light beams **390** are reflected off of the internal target **380**, which provides a depth (z-axis) measurement of the internal target **380**. Since the internal target **380** is at a fixed position, the measured depth of the internal target **380** should not change. Accordingly, any measured change in the position of the internal target **380** reflects changes in internal optics associated with the thermal state of the confocal imaging apparatus.

The light beams **392** project through the window **376** and focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure). Alternatively, the internal target **380** may be included in an imaging apparatus with a flat focal surface (e.g., an imaging apparatus with a field lens). Such an imaging apparatus may or may not be a confocal imaging apparatus. These light beams **392** may be used to measure the position of an object in the FOV of the confocal imaging apparatus. The measured change in the position of the internal target **380** can be used to correct for measurement errors caused by the thermal state. Any apparent change in the z-axis position of the internal target **380** may be used to apply an adjustment factor to other z-axis measurements of the imaged object to compensate for changes in the focusing optics caused by temperature. Additionally, a change in the z-axis position of the internal target may be used to apply an adjustment to the X and Y pixel measurements in embodiments. In one embodiment, the z-axis position of the internal target and measured points of an object are input into a thermal state compensation model to compensate for the thermal state. In one embodiment, the thermal state compensation model is a three dimensional polynomial function.

FIG. **4** is a schematic illustration of a confocal imaging apparatus **450**, in accordance with one embodiment. In one embodiment, the confocal imaging apparatus **450** corresponds to confocal imaging apparatus **20** of FIG. **1**A. In one embodiment, components of confocal imaging apparatus **20** correspond to like named components illustrated in optics **200** of FIG. **2**. In confocal imaging apparatus **450** a parent light beam **452** may be a combination of light emitted by multiple lasers **454**A, **4548** and **4540**. Alternatively, the parent light beam **452** may be produced by a single laser (e.g., **4548**). An illumination module **456** (e.g., an optic expander) then expands the single parent beam into an array of incident light beams **458**. Incident light beams pass through a unidirectional (e.g., unidirectional) mirror or beam splitter **460**, then through focusing optics **462** towards an object **464** to be imaged.

Parent beam **452** may include multiple different wavelengths, with a different wavelength being transmitted from each laser **454**A-C. Thus, parent light beam **452** and one or more incident light beams in the array of light beams **458** may be composed of multiple different light components. Alternatively, each light beam in the array of light beams may include a single wavelength from the multiple wavelengths of parent beam **452**. Lasers **454**A-C may be arranged such that each light beam focuses on a different curved focal surface, P_A, P_B and P_C, respectively. In the position shown in FIG. **4**, incident light beam **458**A reflects oft of the surface at spot **470**A, which in the specific optical arrangement of optics **462** is in the focal point for light component A (emitted by laser **454**A). Thus, a returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel. In one embodiment, the detector is a two-dimensional array of spectrophotometers, e.g. a 3 CHIP COD sensor. Similarly, different maximal intensity will be reached for spots **470**B and **4700** for light components B and C, respectively. Thus, by using different light components each one focused simultaneously at a different plane, the time used to complete a measurement can be reduced as different focal plane ranges can simultaneously be measured.

In an alternative embodiment, only a single wavelength of light is emitted (e.g., by a single laser). Thus, parent beam **452** and the array of light beams **458** may include a single wavelength. In such an embodiment, each of the light beams in the array of light beams **458** focuses on the same curved focal surface P_C. Thus in the position shown in FIG. **4**, incident light beam **458**A reflects off of the surface at spot **470**A which in the specific focusing setting of focusing optics **462** is at the focal point for focusing optics **462**. Thus, the returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel and is registered as the z-axis position for spot **470**C. Similarly, incident light beams **458**A, **458**B reflect off of the surface at spots **470**A and **470**B, respectively. However, the spots **470**A, **470**B are not on the curved focal surface P_C. Accordingly, light is reflected back in a blurred manner from the object **464** for those spots. By changing the focusing setting for focusing optics **462** so that the focal point aligns with spot **470**B and separately with **470**A, corresponding depths associated with those focusing settings may be detected for spots **470**B and **470**A, respectively.

FIG. **5**A is a flow chart showing one embodiment of a method **500** for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface. Method **500** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **500** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment,

at least some operations of method **500** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described in embodiments herein has a non-flat (e.g., curved) focal surface. This curved focal surface introduces inaccuracies in depth measurements of points of a scanned object. For example, a first point of the object at a center of the confocal imaging apparatus' imaging field may be in focus and thus cause a highest intensity measurement at a depth Z_i. However, a second point of the object at an edge of the imaging field that has a same depth as the first point may be in focus and cause a highest intensity measurement at a depth Z_i+X due to the non-flat focal surface, where X represents the difference between the focal point at the center of the imaging field and the focal point at the edge of the imaging field. Thus, the non-flat imaging field will cause measurements of the first and second points to yield different depth values even though they are at the same depth. In one embodiment, calibration method **500** is performed to calibrate the confocal imaging apparatus so that the error introduced by the non-flat focal surface can be eliminated.

At block **505** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the final accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a final desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns.

Various calibration objects may be used, a few examples of which are set forth herein. One example calibration object is a sphere with a very accurate radius on an accurate X-Y-Z stage. Another example calibration object is a flat plate with a grid of horizontal and vertical lines printed on a surface of the plate. A flatness of the plate and the line spacing may be very accurate. Another example calibration object is a flat plate with circles or dots printed on a surface of the plate. The flatness of the plate and the size and spacing of the circles may be very accurate. Many other calibration objects may also be used. FIG. **5**C illustrates one example calibration object **590**, which is a flat plate with a grid of precisely spaced circles or dots.

Referring back to FIG. **5**A, the calibration object is measured at each focusing setting (e.g., encoder position) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object.

In one embodiment, the calibration object is mounted to a calibration jig, which may precisely move the calibration object in one or more dimensions. For example, the calibration object **590** may be mounted to the calibration jig, and the calibration jig may be moved along the z-axis. In one embodiment, the calibration jig moves the calibration object in 1 mm increments, with an accuracy of 1 μm. The calibration jig may move the calibration object in such a way as to cover more than the full field of view of the confocal imaging apparatus (e.g., the calibration object may be larger than the FOV of the confocal imaging apparatus) and to cover more than the range for the depth of scanning of the confocal imaging apparatus.

In the example of the calibration object **590**, the calibration object **590** may be scanned in two ways. A first scan may be performed at each depth position of the calibration object **590** using regular confocal scanning. This will provide a z-position for each dot in the coordinate system of the confocal imaging apparatus (e.g., based on the coordinates of the encoder that positions the lens). A second scan may be performed to generate an image of the dots at focus for each focal setting. The image may be used to determine an X, Y position for the center of each dot in pixel coordinates and with sub-pixel accuracy.

At block **510**, the measurements of the calibration object (measurements of the calibration object's surface topology) are compared to a known surface topology of the calibration object. Each point in the calibration object (e.g., each dot in calibration object **590** having a measured x-pixel, y-pixel and encoder value) may be paired to a corresponding real world point (point in a world coordinate system) from the calibration object, where the world coordinate system corresponds to known X, Y, Z coordinates of the calibration object. For example, the X and Y coordinates for calibration object **590** would correspond to known fixed positions of the dots, and the Z coordinate for calibration object **590** would depend on a setting of a calibration jig. For each point of the calibration object, a difference between a measured depth value and a known depth value may be determined. Additionally, for each point of the calibration object, a difference between a measured X and Y position and a known X and Y position may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **515**, the determined differences of the multiple points may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. The function is referred to herein as a un-distortion function. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature\ (object)}(x,y,Z_{optics})=a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \tag{1}$$

Where x and y are the X, Y coordinates for points on a plane normal to the imaging axis. Alternatively, a higher order polynomial may be used. The smooth function with the solved constants may then be used as an accurate field curvature model. Every parameter may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. This may result in an 18 parameter field curvature model if the above described bivariate quadratic polynomial is used.

Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape). In such an embodiment, a generated model may have a different number of parameters (e.g., 12 parameters if a function describing a conic shape is used). Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS) method) may be applied to find the best values for the constants. As mentioned, this process may be performed for each focusing setting. This is because the amount of field curvature may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate field

curvature model may be generated for each focusing setting. Alternatively, a single field curvature model may be generated that accounts for the changes to the field curvature model due to changes in the focusing setting.

In embodiments, X and Y positions are solved for at the same time that the depth is solved for. For example, differences in X and Y position at different focus settings may also be applied to solve for the constants in the smooth function. Additionally, other types of geometric correction may be solved for as well using this technique. All such geometric corrections may be solved for together. Other types of phenomena that may be corrected for using this technique include magnification change, optical distortion (e.g., non-constant magnification in x and y), optical aberrations, and so on. All such distortions may be solved for together.

FIG. **5**D illustrates a chart **594** showing a distribution of points of the calibration object **590** as measured by the confocal imaging apparatus (in the coordinate system of the confocal imaging apparatus). Chart **594** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots appear to lie on a curved surface. FIG. **5**E illustrates a chart **597** showing a distribution of points in the real world. Chart **597** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots lie on a plane. After calibration, the transformation for each dot may be determined to correct for optical distortions. Thus, the true world position of each dot may be accurately measured.

At block **525**, a temperature dependence of the confocal imaging apparatus (e.g., the focusing optics and of a lens housing for the focusing optics) is determined. In one embodiment, the operations of one or more of blocks **505-515** are performed at multiple temperatures over a temperature operating range of the confocal imaging apparatus to determine the temperature dependence. Changes in temperature may cause differences in the measured depth values. Accordingly, a temperature dependency may be determined and applied to the field curvature model to create a thermal state correction model. For example, the field curvature model may be modified from x, y, z=F(i, j, encoder) to x, y, z=F(i, j, encoder, T_{state}), where x, y and z represent real world coordinates, i represents an x-pixel, j represents a y-pixel, encoder represents a focal setting (encoder position), and T_{state} represents a thermal state. For such a model that takes into account the thermal state, an estimate of the thermal state should be obtained for each measurement. A thermal state correction model may also be generated for an imaging apparatus with a flat focal surface using the same process as described herein for an imaging apparatus with a curved focal surface.

In one embodiment, opto-mechanical simulation is performed to determine a relationship between temperature and adjustments in calibration of the focusing optics. This relationship may be used to determine a correction that may be applied to all parameters of the generated field curvature model or models, where the amount of correction is based on a current temperature.

In one embodiment, the main change in the focusing optics due to temperature is a focus shift. Curvature of the non-flat focal surface may be practically unchanged by changes in temperature. In one embodiment, a shift in focus for focusing settings may be determined by scanning one or more elements (e.g., an internal target such as internal target **380** of FIGS. **3**C-**3**D) of the confocal imaging apparatus that is near or along the optical path. In one embodiment, the scanned element is on a side of a field of view (FOV) of the confocal imaging apparatus. This element may be kept at the same distance relative to one or more components of the focusing optics. With each scan, when the 3D surface of an object is captured, the edge of the FOV where the internal target is located captures a position of the internal target. Due to the fact that the internal target is part of the confocal imaging apparatus and has a fixed position, detected changes in the position of the internal target are caused by changes in the thermal state. Accordingly, if a focus shift of the internal target is detected from the scan, then an adjustment factor may be applied to the field curvature model to compensate for the thermal state.

In one embodiment, separate field curvature models are generated for each temperature value or range of the confocal imaging apparatus at a particular focusing setting. Alternatively, a single model may be generated for each focusing setting that accounts for changes in temperature. Alternatively, a temperature dependent adjustment factor may be determined and applied to the field curvature model or models based on a measured temperature.

In one embodiment, a simple model may be used that assumes that optical change caused by the thermal state is primarily due to a linear shift in the focal setting (e.g., a backward motion in the encoder position). For such a model, changes caused by the thermal state may be corrected by adding the difference between a current measured internal target position and a reference value to every focal setting (encoder value) before applying the un-distortion function. The simple model may have the form of:

$$x,y,z=F(i,j,\text{encoder}-(\text{internal target position}-\text{reference target position})) \quad (2)$$

where F is the un-distortion function, such as function (1) above.

In another embodiment, a more complex model is used that assumes internal target effects are caused by the focal shift of encoder, but in a complex way. Such a model may have the form of:

$$x,y,z=F(i,j,f(\text{encoder},\text{internal target position})) \quad (3)$$

In another embodiment, a model that corrects for distortions caused by the thermal state assumes that the thermal state changes all optics by a small amount that can be linearly estimated. Such a model may have the form of:

$$x, y, z = F_{hot}(i, j, \text{encoder})\frac{(p-a)}{(b-a)} + F_{cold}(i, j, \text{encoder})\left(1 - \frac{(p-a)}{(b-a)}\right) \quad (4)$$

where F_{hot} is the un-distortion function under a hot condition, F_{cold} is the un-distortion function under a cold condition, a is the internal target position in the hot condition, b is the internal target position in the cold position, and p is the measured internal target position.

At block **535**, the one or more generated field curvature models for the confocal imaging apparatus are stored. The field curvature models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the field curvature models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The Field curvature model (or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface of the confocal imaging apparatus. If calibration information is stored in memory of the confocal imaging apparatus, then

the field curvature models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received field curvature models to correct for the field curvature of the confocal imaging apparatus.

FIG. **5**B is a flow chart showing one embodiment of a method **550** for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification. Method **550** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **550** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment, at least some operations of method **550** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described with reference to method **550** may have a non-flat (e.g., curved) focal surface or a flat focal plane. Moreover, the confocal imaging apparatus described with reference to method **550** has focusing optics that are configured so that changes in a focusing setting cause a change in magnification at the focal surface or focal plane. This change in magnification introduces inaccuracies in X and Y position measurements of points of a scanned object. For example, a point of the object might be measured to have a first X and Y position at a first focusing setting, but might be measured to have a second X and Y position at a second focusing setting. Thus, the magnification changes will cause measurements to yield different X, Y values as the focusing setting changes. In one embodiment, calibration method **550** is performed to calibrate the confocal imaging apparatus so that the inaccuracies introduced by the changes in magnification can be eliminated.

At block **555** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the final accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a final desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns. Any of the calibration objects described with reference to FIG. **5**A may be used.

The calibration object is measured at each focusing setting (encoder value) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object. Based on these measurements, a list of coordinates is collected in both the calibration object space (e.g., real world) and in the sensor/optics space (e.g., virtual space). In the calibration object space, each set of coordinates for a point of the object has an X_{obj}, Y_{obj} and Z_{obj} coordinate. These coordinates are known to be accurate due to the known information about the calibration object. In the sensor/optics space, each set of coordinates for a point of the object includes an X_{pix}, Y_{pix}, Z_{optics} coordinate, where X_{pix} and Y_{pix} are determined based on the pixel detecting the point and Z_{optics} is the lens position of the focusing optics (e.g., the focusing setting).

At block **560**, the measurements of the calibration object (measurements of the calibration object's surface topology) may be compared to a known surface topology of the calibration object. For each point of the calibration object, a difference between a measured depth value, X value and/or Y value and a known depth value, X value and/or Y value may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **562**, it is determined whether the focusing optics have a curved focal surface. If the focusing optics do have a curved focal surface, the method proceeds to block **565**. Otherwise the method proceeds to block **570**.

At block **565**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature\ (object)}(x,y,Z_{optics})=a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \quad (5)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape), such as a polynomial of higher order. The smooth function with the solved constants may then be used for an accurate field curvature model.

At block **570**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional or higher dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on an x-axis caused by changes in the focusing setting (e.g., changes in the Z_{optics} value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$X_{Object}(x,Z_{optics})=b_1x^2+b_2y^2+b_3x+b_4y+b_5xy+b_6 \quad (6)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the X coordinate.

At block **575**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on a y-axis caused by changes in the focusing setting (e.g., changes in the Z_{optics} value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Y_{Object}(x,y,Z_{optics})=c_1x^2+c_2y^2+c_3x+c_4y+c_5xy+c_6 \quad (7)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function

(e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the Y coordinate.

Blocks **565**, **570** and **575** have been described as three separate operations. However, in some embodiments a single operation may be performed to solve for each of the x-coordinate, the y-coordinate and the z-coordinate. For example, an un-distortion function having the following form may be solved to determine the x, y and z coordinates.

$$F_X(x,y,z)=a_0+a_1x+a_2y+a_3z+a_4x^2+a_5y^2+a_6z^2+\ldots+a_ixy+\ldots+a_jx^ny^mz^k$$

$$F_Y(x,y,z)=b_0+b_1x+b_2y+b_3z+b_4x^2+b_5y^2+b_6z^2+\ldots+b_ixy+\ldots+b_jx^ny^mz^k$$

$$F_Z(x,y,z)=c_0+c_1x+c_2y+c_3z+c_4x^2+c_5y^2+c_6z^2+\ldots+c_ixy+\ldots+c_jx^ny^mz^k \tag{8}$$

where F_X, F_Y and F_Z are the functions whose results in world coordinates are to be solved for, x and y are pixel coordinates measured by the confocal imaging apparatus, z is a focal setting (e.g., encoder coordinates corresponding to a focal setting), a_i, b_i and c_i are learned parameters, and n, m and k are the maximal degree of the nominal. The function may be selected to minimize a mean square error between the world coordinates and the found positions after the function transformation. Outlier positions may be detected and removed before fitting. In one embodiment, a number of non-zero parameters is constrained.

At block **580**, one or more optics correcting models are generated based on the first second and third polynomial functions (or other smooth functions), such as those represented in equations 5-8. Every parameter for equations 5-8 may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. In one embodiment, each parameter is modeled as a quadratic change to the Z_{optics} (focusing setting). For example, parameter a_1 may be a parameter having a form:

$$a_1(Z_{Optics})=A+B*Z_{Optics}+C*Z_{Optics}^2 \tag{9}$$

Parameters a_2–a_6, b_1–b_6 and c_1–c_6 may be similarly represented. This may result in a 54 parameter model that corrects for full curvature, magnification and distortion of the field of view (FOV).

Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS) method) may be applied to find the best values for the constants at each of blocks **565**, **570** and **575**. As mentioned, these processes may be performed for each focusing setting. This is because the amount of field curvature and magnification may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate model may be generated for each focusing setting. Alternatively, a single model may be generated that accounts for the changes to the model due to changes in the focusing setting. Note that temperature dependence may also be determined and included in the model as described with reference to block **525** of method **500**. In one embodiment, a temperature dependence is determined, and a model that corrects for thermal state is created, as discussed above with reference to method **500**.

At block **585**, the one or more generated models for the confocal imaging apparatus are stored. The models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The model (or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface as well as to correct for inaccuracies caused by changes in magnification. If calibration information is stored in memory of the confocal imaging apparatus, then the models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received models to correct for the field curvature and/or magnification changes of the confocal imaging apparatus.

FIG. **6** is a flow chart showing one embodiment of a method **600** for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model or other model (e.g., a thermal state compensation model) calibrated to a confocal imaging apparatus or other imaging apparatus (e.g., a stereoscopic imaging apparatus). Method **600** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **600** are performed by a computing device (e.g., computing device **24** of FIG. **1B** executing image processing module **82**).

At block **605** of method **600**, processing logic receives intensity measurements generated by pixels of a detector of a confocal imaging apparatus. The detector may have a two-dimensional array of pixels, and each pixel may receive a particular light beam of an array of light beams directed at the detector. The array of light beams may be an array of returning light beams that have been reflected off of a surface of the imaged three dimensional object. Thus, each pixel of the detector is associated with a particular point of the three dimensional object and provides intensity measurements for an associated returning light beam from the array of returning light beams.

Each received intensity measurement is associated with a particular focusing setting of the confocal imaging apparatus. Intensity measurements may be received over a range of focusing settings. At block **620**, processing logic determines, for each pixel, a focusing setting of the confocal imaging apparatus that provides a maximum measured intensity.

A relative distance between a probe of the confocal imaging apparatus and a focal point of the confocal imaging apparatus may be known for each focusing setting (encoder value). A point of the imaged object is known to be in focus (e.g., at the focal point) when a measured intensity for that point is maximal. Accordingly, at block **630** processing logic determines, for each pixel, a depth of a point of the three dimensional object associated with that pixel that corresponds to the focusing setting that yielded the maximal intensity. If the imaging apparatus includes an internal target in the FOV of the imaging apparatus, then some pixels will be associated with points on the internal target. Accordingly, a depth of the points of the internal target may also be determined.

As discussed previously herein, the non-flat focal surface and/or magnification changes of the confocal imaging apparatus introduce an error in the depth measurements and/or in the X, Y coordinate measurements. Accordingly, at block **640** processing logic adjusts the determined depths of points of the imaged three dimensional object based on applying the determined focusing settings for the pixels associated with those points to a field curvature model. Processing logic

may additionally or alternatively determine X, Y coordinates of the points based on applying the determined focusing settings to the field curvature model or other model. One or more field curvature models and/or other models may be used. For example, a particular field curvature model and/or other model may be associated with each focusing setting. An appropriate field curvature model may be identified based on the focusing setting at which a point on the object came into focus. A particular depth adjustment for that point may then be determined by providing the X, Y coordinates of the pixel into the determined field curvature model. Alternatively, a single field curvature model may be used, and the X, Y coordinates and focusing setting may be input into the field curvature model to determine the depth displacement. In one embodiment, a temperature of the focusing optics is also measured and/or a thermal state is otherwise determined (e.g., using an internal target position), and an additional depth adjustment factor (and/or other optical adjustment) is determined based on the temperature (e.g., using a thermal state compensation model). This additional depth adjustment factor (and/or additional optical adjustment) may then be applied to the measured depths (and/or X and Y coordinates) of all points. In one embodiment, a single model is used that compensates for both the thermal state and field curvature.

At block **650**, processing logic may determine a shape (e.g., surface topology) of the three dimensional object based on the adjusted depths and/or x and y coordinates. Processing logic may then create an accurate virtual three dimensional model of the imaged object.

FIG. **7** illustrates a diagrammatic representation of a machine in the example form of a computing device **700** within which a set of instructions, for causing the machine to perform any one or more of the methodologies discussed herein, may be executed. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet computer, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein. In one embodiment, computing device **700** corresponds to computing device **24** of FIG. **1**B.

The example computing device **700** includes a processing device **702**, a main memory **704** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM), etc.), a static memory **706** (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory (e.g., a data storage device **728**), which communicate with each other via a bus **708**.

Processing device **702** represents one or more general-purpose processors such as a microprocessor, central processing unit, or the like. More particularly, the processing device **702** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processing device **702** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. Processing device **702** is configured to execute the processing logic (instructions **726**) for performing operations and steps discussed herein.

The computing device **700** may further include a network interface device **722** for communicating with a network **764** or other device. The computing device **700** also may include a video display unit **710** (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), an alphanumeric input device **712** (e.g., a keyboard), a cursor control device **714** (e.g., a mouse), and a signal generation device **720** (e.g., a speaker).

The data storage device **728** may include a machine-readable storage medium (or more specifically a non-transitory computer-readable storage medium) **724** on which is stored one or more sets of instructions **726** embodying any one or more of the methodologies or functions described herein. A non-transitory storage medium refers to a storage medium other than a carrier wave. The instructions **726** may also reside, completely or at least partially, within the main memory **704** and/or within the processing device **702** during execution thereof by the computer device **700**, the main memory **704** and the processing device **702** also constituting computer-readable storage media.

The computer-readable storage medium **724** may also be used to store a field compensator **750** which may correspond to field compensator **92** of FIG. **1**B. The computer readable storage medium **724** may also store a software library containing methods that call the field compensator **750**. While the computer-readable storage medium **724** is shown in an example embodiment to be a single medium, the term "computer-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "computer-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present invention. The term "computer-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent upon reading and understanding the above description. Although embodiments of the present invention have been described with reference to specific example embodiments, it will be recognized that the invention is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the

optical system comprises a non-flat focal surface, and wherein the optical system comprises focusing optics to perform focusing of the light onto the non-flat focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to thereby adjust a focusing setting of the optical system and displace the non-flat focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, and wherein at least one of a shape or a magnification of the non-flat focal surface changes with changes in the focusing setting; and

a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the returning light are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the non-flat focal surface using one or more compensation models that provide different adjustments for different focusing settings of the optical system.

2. The imaging apparatus of claim **1**, wherein the non-flat focal surface comprises a curved focal plane and the detected positions for the one or more of the plurality of points are to be adjusted to compensate for a curvature of the curved focal plane.

3. The imaging apparatus of claim **1**, further comprising:

a beam splitter disposed along the optical path between the light source and the focusing optics, wherein the beam splitter directs the light from the light source towards the focusing optics and directs the returning light from the focusing optics to the detector;

wherein the imaging apparatus is characterized in having an absence of a field lens between the beam splitter and the light source.

4. The imaging apparatus of claim **3**, wherein the imaging apparatus is further characterized in having an absence of a field lens between the beam splitter and the detector.

5. The imaging apparatus of claim **3**, wherein the light source comprises an illumination module configured to generate an array of light in an x-y plane.

6. The imaging apparatus of claim **1**, further comprising:

a folding prism along the optical path of the light after the focusing optics, wherein the folding prism is to direct the light onto the three dimensional object to be imaged;

wherein the plurality of lenses comprise:

a first lens group;

a second lens group disposed proximate to the folding prism, the second lens group having a fixed location relative to the first lens group; and

a third lens group disposed between the first lens group and the second lens group, the third lens group having a variable location that is adjustable by the translation mechanism, wherein the focusing optics comprises the third lens group.

7. The imaging apparatus of claim **1**, wherein a radius of a largest lens of the plurality of lenses is less than 13 millimeters.

8. The imaging apparatus of claim **1**, wherein the imaging apparatus is a confocal imaging apparatus, and wherein the optical system is a confocal optical system, the imaging apparatus further comprising a processor to:

determine a location of the at least one lens that yields a maximum measured intensity for a portion of the returning light;

determine a position on the imaging axis of a point of the three dimensional object illuminated by the portion of the returning light that corresponds to the determined location of the at least one lens; and

adjust the position on the imaging axis of the point of the three dimensional object based on applying the determined location of the at least one lens to a field curvature model that is calibrated to the imaging apparatus to compensate for the non-flat focal surface.

9. The imaging apparatus of claim **1**, wherein the optical system is a non-telecentric optical system.

10. The imaging apparatus of claim **8**, further comprising:

one or more elements near or along the optical path, the one or more elements having a fixed distance from a first lens of the plurality of lenses, wherein the fixed distance changes with changes in temperature, wherein the processor is further to:

determine a current distance between the one or more elements and the first lens; and

apply an adjustment factor to the field curvature model based on the current distance.

11. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light comprising a plurality of light beams;

optics comprising a plurality of lenses disposed along an optical path of the light, wherein the optics comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity, and wherein the optics are characterized by an absence of a field lens, wherein the field lens is a diverging lens that opens rays of the plurality of light beams;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics; and

a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the returning light are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for the absence of the field lens.

12. The imaging apparatus of claim **11**, wherein the absence of the field lens causes the focusing optics to perform the focusing of the light onto a non-flat focal surface.

13. The imaging apparatus of claim **12**, wherein the non-flat focal surface comprises a curved focal plane, wherein the detected positions for the one or more of the plurality of points are to be adjusted to compensate for a curvature of the curved focal plane, and wherein a shape of the non-flat focal surface changes with changes in the location of the at least one lens.

14. The imaging apparatus of claim **11**, further comprising:

a beam splitter disposed along the optical path between the light source and the focusing optics, wherein the beam splitter directs the light from the light source

towards the focusing optics and directs the returning light from the focusing optics to the detector.

15. The imaging apparatus of claim 14, wherein the light source comprises an illumination module configured to generate an array of light in an x-y plane.

16. The imaging apparatus of claim 12, further comprising:

a folding prism along the optical path of the light after the focusing optics, wherein the folding prism is to direct the light onto the three dimensional object to be imaged;

wherein the plurality of lenses comprise:

a first lens group;

a second lens group disposed proximate to the folding prism, the second lens group having a fixed location relative to the first lens group; and

a third lens group disposed between the first lens group and the second lens group, the third lens group having a variable location that is adjustable by the translation mechanism, wherein the focusing optics comprises the third lens group.

17. The imaging apparatus of claim 11, wherein a radius of a largest lens of the plurality of lenses is less than 13 millimeters.

18. The imaging apparatus of claim 11, wherein the imaging apparatus is a confocal imaging apparatus, and wherein the optics are confocal optics, the imaging apparatus further comprising a processor to:

determine locations of the at least one lens that yields yield a maximum measured intensity for portions of the returning light;

determine positions on the imaging axis of points of the three dimensional object illuminated by the portions of the returning light that corresponds correspond to the determined locations of the at least one lens; and

adjust the positions on the imaging axis of the points of the three dimensional object based on applying the determined locations of the at least one lens to one or more field curvature models that are calibrated to the imaging apparatus to compensate for the absence of the field lens, wherein the one or more field curvature models provide different adjustments for different locations of the at least one lens.

19. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

a non-telecentric optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the non-telecentric optical system comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity, the focusing optics comprising at least one lens of the plurality of lenses;

a translation mechanism to adjust a location of the at least one lens to displace the focal surface along an imaging axis defined by the optical path, wherein adjustments to the location of the at least one lens cause a change in magnification of the focal surface; and

a detector to measure intensities of returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the intensities of the returning light are to be measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object, wherein detected positions of one or more of the plurality of points are to be adjusted to compensate for respective magnifications of the focal surface associated with respective locations of the plurality of locations of the at least one lens.

20. The imaging apparatus of claim 19, wherein the focusing optics perform the focusing of the light onto a non-flat focal surface.

21. The imaging apparatus of claim 20, wherein the non-flat focal surface comprises a curved focal plane, wherein the detected positions for the one or more of the plurality of points are to be adjusted to compensate for a curvature of the curved focal plane, and wherein a shape of the non-flat focal surface changes with changes in the location of the at least one lens.

22. The imaging apparatus of claim 19, further comprising:

a beam splitter disposed along the optical path between the light source and the focusing optics, wherein the beam splitter directs the light from the light source towards the focusing optics and directs the returning light from the focusing optics to the detector;

wherein the imaging apparatus is characterized in having an absence of a field lens between the beam splitter and the light source, and is further characterized in having an absence of a field lens between the beam splitter and the detector.

23. The imaging apparatus of claim 22, wherein the light source comprises an illumination module configured to generate an array of light beams in an x-y plane, wherein the imaging apparatus is a confocal imaging apparatus, and wherein the non-telecentric optical system is a confocal optical system.

24. The imaging apparatus of claim 19, wherein the light source comprises a semiconductor laser unit.

25. The imaging apparatus of claim 19, further comprising:

a folding prism along the optical path of the light after the focusing optics, wherein the folding prism is to direct the light onto the three dimensional object to be imaged;

wherein the plurality of lenses comprise:

a first lens group;

a second lens group disposed proximate to the folding prism, the second lens group having a fixed location relative to the first lens group; and

a third lens group disposed between the first lens group and the second lens group, the third lens group having a variable location that is adjustable by the translation mechanism, wherein the focusing optics comprises the third lens group.

26. The imaging apparatus of claim 19, wherein a radius of a largest lens of the plurality of lenses is less than 13 millimeters.

27. A method of performing an intraoral scan, comprising:

providing light;

directing, via an optical system comprising a non-flat focal surface, the light toward a three dimensional object to be imaged in an oral cavity;

performing focusing of the light onto the non-flat focal surface using focusing optics comprising a plurality of lenses disposed along an optical path of the light;

adjusting a location of at least one lens of the plurality of lenses to displace the non-flat focal surface along an imaging axis defined by the optical path using a translation mechanism;

measuring intensities of returning light that is reflected off of the three dimensional object and directed back

through the focusing optics, wherein the intensities of the returning light are measured for a plurality of locations of the at least one lens for determination of positions on the imaging axis of a plurality of points of the three dimensional object; and

adjusting detected positions of one or more of the plurality of points to compensate for the non-flat focal surface using one or more compensation models that provide different adjustments for different focusing settings of the focusing optics.

28. The method of claim **27**, wherein the focusing comprises confocal focusing, the method further comprising:

determining a location of the at least one lens that yields a maximum measured intensity for a portion of the returning light;

determining a position on the imaging axis of a point of the three dimensional object illuminated by the portion of the returning light that corresponds to the determined location of the at least one lens; and

adjusting the position on the imaging axis of the point of the three dimensional object based on applying the determined location of the at least one lens to a field curvature model that is calibrated to compensate for the non-flat focal surface.

29. The method of claim **28**, wherein the field curvature model comprises a three dimensional polynomial function.

30. The method of claim **27**, wherein the non-flat focal surface comprises a curved focal plane and the detected positions for the one or more of the plurality of points are adjusted to compensate for a curvature of the curved focal plane.

* * * * *

EXHIBIT 3

US010507089B2

(12) **United States Patent**
Verker et al.

(10) **Patent No.: US 10,507,089 B2**
(45) **Date of Patent: Dec. 17, 2019**

(54) **IMAGING APPARATUS WITH SIMPLIFIED OPTICAL DESIGN**

(71) Applicant: **Align Technology, Inc.**, San Jose, CA (US)

(72) Inventors: **Tal Verker**, Ofra (IL); **Adi Levin**, Nes Tziona (IL); **Ofer Saphier**, Rechovot (IL); **Maayan Moshe**, Ra'anana (IL)

(73) Assignee: **Align Technology, Inc.**, San Jose, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/396,484**

(22) Filed: **Apr. 26, 2019**

(65) **Prior Publication Data**

US 2019/0247164 A1 Aug. 15, 2019

Related U.S. Application Data

(60) Continuation of application No. 16/286,437, filed on Feb. 26, 2019, which is a continuation of application

(Continued)

(51) **Int. Cl.**
A61C 9/00 (2006.01)
G01B 11/24 (2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***A61C 9/0066*** (2013.01); ***G01B 11/24*** (2013.01); ***G02B 21/006*** (2013.01);

(Continued)

(58) **Field of Classification Search**
CPC A61C 9/0066; G01B 11/24; G02B 21/006; G02B 23/2446; G02B 23/2461; G02B 23/26; G02B 27/0025

(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,171,695 A 9/1939 Harper
2,467,432 A 4/1949 Kesling

(Continued)

FOREIGN PATENT DOCUMENTS

AU 3031677 A 5/1979
AU 3031677 B 7/1981

(Continued)

OTHER PUBLICATIONS

Kleeman et al., "The Speed Positioner", J. Clin. Orthod.; 30(12); pp. 673-680; Dec. 1996.

(Continued)

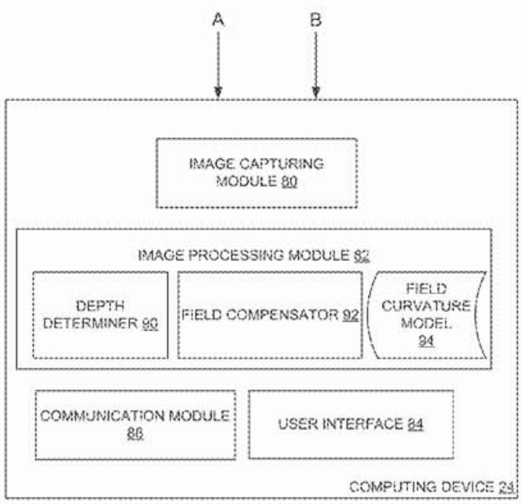
Primary Examiner — Tri T Ton

(74) *Attorney, Agent, or Firm* — Lowenstein Sandler LLP

(57) **ABSTRACT**

A method of generating a three-dimensional virtual model of an intraoral object includes capturing, by an imaging apparatus for performing intraoral scans, surface scan data of the intraoral object while changing a position of at least one lens of focusing optics of the imaging apparatus, wherein the surface scan data comprises depth data for a plurality of points of the intraoral object. The method further includes adjusting the depth data for one or more of the plurality of points based at least in part on the position of the at least one lens associated with the depth data for the one or more of the plurality of points. The method further includes generating the three-dimensional virtual model of the intraoral object using the adjusted depth data.

33 Claims, 13 Drawing Sheets



Related U.S. Application Data

No. 15/610,515, filed on May 31, 2017, now Pat. No. 10,327,872, which is a division of application No. 14/825,173, filed on Aug. 13, 2015, now Pat. No. 9,675,430.

(60) Provisional application No. 62/037,778, filed on Aug. 15, 2014.

(51) **Int. Cl.**

G02B 23/24 (2006.01)
G02B 21/00 (2006.01)
G02B 27/00 (2006.01)
G02B 23/26 (2006.01)

(52) **U.S. Cl.**

CPC ***G02B 23/2446*** (2013.01); ***G02B 23/2461*** (2013.01); ***G02B 23/26*** (2013.01); ***G02B 27/0025*** (2013.01)

(58) **Field of Classification Search**

USPC 356/600–640
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,531,222 A 11/1950 Kesling
3,379,193 A 4/1968 Monsghan
3,385,291 A 5/1968 Martin
3,407,500 A 10/1968 Kesling
3,478,742 A 11/1969 Bohlmann
3,496,936 A 2/1970 Gores
3,533,163 A 10/1970 Kirschenbaum
3,556,093 A 1/1971 Quick
3,600,808 A 8/1971 Reeve
3,660,900 A 5/1972 Andrews
3,683,502 A 8/1972 Wallshein
3,738,005 A 6/1973 Cohen
3,860,803 A 1/1975 Levine
3,885,310 A 5/1975 Northcutt
3,916,526 A 11/1975 Schudy
3,922,786 A 12/1975 Lavin
3,950,851 A 4/1976 Bergersen
3,983,628 A 10/1976 Acevedo
4,014,096 A 3/1977 Dellinger
4,195,046 A 3/1980 Kesling
4,253,828 A 3/1981 Coles et al.
4,255,138 A 3/1981 Frohn
4,324,546 A 4/1982 Heitlinger et al.
4,324,547 A 4/1982 Arcan et al.
4,348,177 A 9/1982 Kurz
4,419,992 A 12/1983 Chorbajian
4,433,956 A 2/1984 Witzig
4,478,580 A 10/1984 Barrut
4,500,294 A 2/1985 Lewis
4,505,673 A 3/1985 Yoshii
4,519,386 A 5/1985 Sullivan
4,526,540 A 7/1985 Dellinger
4,575,330 A 3/1986 Hull
4,575,805 A 3/1986 Moermann et al.
4,591,341 A 5/1986 Andrews
4,609,349 A 9/1986 Cain
4,611,288 A 9/1986 Duret et al.
4,656,860 A 4/1987 Orthuber et al.
4,663,720 A 5/1987 Duret et al.
4,664,626 A 5/1987 Kesling
4,676,747 A 6/1987 Kesling
4,755,139 A 7/1988 Abbatte et al.
4,757,824 A 7/1988 Chaumet
4,763,791 A 8/1988 Halverson et al.
4,764,111 A 8/1988 Knierim
4,793,803 A 12/1988 Martz
4,798,534 A 1/1989 Breads
4,836,778 A 6/1989 Baumrind et al.
4,837,732 A 6/1989 Brandestini et al.
4,850,864 A 7/1989 Diamond
4,850,865 A 7/1989 Napolitano
4,856,991 A 8/1989 Breads et al.
4,877,398 A 10/1989 Kesling
4,880,380 A 10/1989 Martz
4,886,451 A 12/1989 Cetlin
4,889,238 A 12/1989 Batchelor
4,890,608 A 1/1990 Steer
4,935,635 A 6/1990 O'Harra
4,936,862 A 6/1990 Walker et al.
4,937,928 A 7/1990 van der Zel
4,941,826 A 7/1990 Loran et al.
4,952,928 A 8/1990 Carroll et al.
4,964,770 A 10/1990 Steinbichler et al.
4,975,052 A 12/1990 Spencer et al.
4,983,334 A 1/1991 Adell
4,997,369 A 3/1991 Shafir
5,002,485 A 3/1991 Aagesen
5,011,405 A 4/1991 Lemchen
5,017,133 A 5/1991 Miura
5,027,281 A 6/1991 Rekow et al.
5,035,613 A 6/1991 Breads et al.
5,037,295 A 8/1991 Bergersen
5,055,039 A 10/1991 Abbatte et al.
5,100,316 A 3/1992 Wildman
5,103,838 A 4/1992 Yousif
5,121,333 A 6/1992 Riley et al.
5,123,425 A 6/1992 Shannon, Jr. et al.
5,128,870 A 7/1992 Erdman et al.
5,130,064 A 7/1992 Smalley et al.
5,131,843 A 7/1992 Hilgers et al.
5,131,844 A 7/1992 Marinaccio et al.
5,139,419 A 8/1992 Andreiko et al.
5,145,364 A 9/1992 Martz et al.
5,176,517 A 1/1993 Truax
5,204,670 A 4/1993 Stinton
5,242,304 A 4/1993 Truax et al.
5,245,592 A 9/1993 Kuemmel et al.
5,273,429 A 12/1993 Rekow et al.
5,278,756 A 1/1994 Lemchen et al.
5,306,144 A 4/1994 Hibst et al.
5,328,362 A 7/1994 Watson et al.
5,335,657 A 8/1994 Terry, Jr. et al.
5,338,198 A 8/1994 Wu et al.
5,340,309 A 8/1994 Robertson
5,342,202 A 8/1994 Deshayes
5,368,478 A 11/1994 Andreiko et al.
5,372,502 A 12/1994 Massen et al.
5,382,164 A 1/1995 Stern
5,395,238 A 3/1995 Andreiko et al.
5,431,562 A 7/1995 Andreiko et al.
5,440,326 A 8/1995 Quinn
5,440,496 A 8/1995 Andersson et al.
5,447,432 A 9/1995 Andreiko et al.
5,452,219 A 9/1995 Dehoff et al.
5,454,717 A 9/1995 Andreiko et al.
5,456,600 A 10/1995 Andreiko et al.
5,474,448 A 12/1995 Andreiko et al.
RE35,169 E 3/1996 Lemchen et al.
5,499,633 A 3/1996 Fenton
5,528,735 A 6/1996 Strasnick et al.
5,533,895 A 7/1996 Andreiko et al.
5,542,842 A 8/1996 Andreiko et al.
5,543,780 A 8/1996 McAuley et al.
5,549,476 A 8/1996 Stern
5,562,448 A 10/1996 Mushabac
5,570,182 A 10/1996 Nathel et al.
5,587,912 A 12/1996 Andersson et al.
5,605,459 A 2/1997 Kuroda et al.
5,607,305 A 3/1997 Andersson et al.
5,614,075 A 3/1997 Andre, Sr.
5,621,648 A 4/1997 Crump
5,626,537 A 5/1997 Danyo et al.
5,645,420 A 7/1997 Bergersen
5,645,421 A 7/1997 Slootsky
5,651,671 A 7/1997 Seay et al.
5,655,653 A 8/1997 Chester
5,659,420 A 8/1997 Wakai et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,683,243	A	11/1997	Andreiko et al.
5,683,244	A	11/1997	Truax
5,691,539	A	11/1997	Pfeiffer
5,692,894	A	12/1997	Schwartz et al.
5,725,376	A	3/1998	Poirier
5,725,378	A	3/1998	Wang
5,737,084	A	4/1998	Ishihara
5,740,267	A	4/1998	Echerer et al.
5,742,700	A	4/1998	Yoon et al.
5,769,631	A	6/1998	Williams
5,774,425	A	6/1998	Ivanov et al.
5,790,242	A	8/1998	Stern et al.
5,799,100	A	8/1998	Clarke et al.
5,800,174	A	9/1998	Andersson
5,816,800	A	10/1998	Brehm et al.
5,818,587	A	10/1998	Devaraj et al.
5,823,778	A	10/1998	Schmitt et al.
5,848,115	A	12/1998	Little et al.
5,857,853	A	1/1999	van Nifterick et al.
5,866,058	A	2/1999	Batchelder et al.
5,879,158	A	3/1999	Doyle et al.
5,880,961	A	3/1999	Crump
5,880,962	A	3/1999	Andersson et al.
5,904,479	A	5/1999	Staples
5,934,288	A	8/1999	Avila et al.
5,957,686	A	9/1999	Anthony
5,964,587	A	10/1999	Sato
5,971,754	A	10/1999	Sondhi et al.
5,975,893	A	11/1999	Chishti et al.
5,980,246	A	11/1999	Ramsay et al.
5,989,023	A	11/1999	Summer et al.
6,044,309	A	3/2000	Honda
6,049,743	A	4/2000	Baba
6,053,731	A	4/2000	Heckenberger
6,068,482	A	5/2000	Snow
6,099,303	A	8/2000	Gibbs et al.
6,099,314	A	8/2000	Kopelman et al.
6,123,544	A	9/2000	Cleary
6,152,731	A	11/2000	Jordan et al.
6,154,676	A	11/2000	Levine
6,183,248	B1	2/2001	Chishti et al.
6,186,780	B1	2/2001	Hibst et al.
6,190,165	B1	2/2001	Andreiko et al.
6,200,133	B1	3/2001	Kittelsen
6,201,880	B1	3/2001	Elbaum et al.
6,212,435	B1	4/2001	Lattner et al.
6,217,334	B1	4/2001	Hultgren
6,231,338	B1	5/2001	de Josselin de Jong et al.
6,239,705	B1	5/2001	Glen
6,243,601	B1	6/2001	Wist
6,263,234	B1	7/2001	Engelhardt et al.
6,299,438	B1	10/2001	Sahagian et al.
6,309,215	B1	10/2001	Phan et al.
6,315,553	B1	11/2001	Sachdeva et al.
6,328,745	B1	12/2001	Ascherman
6,334,073	B1	12/2001	Levine
6,350,120	B1	2/2002	Sachdeva et al.
6,364,660	B1	4/2002	Durbin
6,382,975	B1	5/2002	Poirier
6,402,510	B1	6/2002	Williams
6,402,707	B1	6/2002	Ernst
6,405,729	B1	6/2002	Thornton
6,436,058	B1	8/2002	Krahner et al.
6,450,807	B1	9/2002	Chishti et al.
6,482,298	B1	11/2002	Bhatnagar
6,499,995	B1	12/2002	Schwartz
6,515,593	B1	2/2003	Stark et al.
6,516,805	B1	2/2003	Thornton
6,520,772	B2	2/2003	Williams
6,524,101	B1	2/2003	Phan et al.
6,540,707	B1	4/2003	Stark et al.
6,572,372	B1	6/2003	Phan et al.
6,573,998	B2	6/2003	Cohen-Sabban
6,594,539	B1	7/2003	Geng
6,597,934	B1	7/2003	de Jong et al.
6,602,070	B2	8/2003	Miller et al.
6,611,783	B2	8/2003	Kelly, Jr. et al.
6,613,001	B1	9/2003	Dworkin
6,616,579	B1	9/2003	Reinbold et al.
6,623,698	B2	9/2003	Kuo
6,624,752	B2	9/2003	Klitsgaard et al.
6,626,180	B1	9/2003	Kittelsen et al.
6,640,128	B2	10/2003	Vilsmeier et al.
6,697,164	B1	2/2004	Babayoff et al.
6,702,765	B2	3/2004	Robbins et al.
6,702,804	B1	3/2004	Ritter et al.
6,705,863	B2	3/2004	Phan et al.
6,830,450	B2	12/2004	Knopp et al.
6,885,464	B1	4/2005	Pfeiffer et al.
6,890,285	B2	5/2005	Rahman et al.
7,036,514	B2	5/2006	Heck
7,092,107	B2	8/2006	Babayoff et al.
7,106,233	B2	9/2006	Schroeder et al.
7,112,065	B2	9/2006	Kopelman et al.
7,121,825	B2	10/2006	Chishti et al.
7,138,640	B1	11/2006	Delgado et al.
7,142,312	B2	11/2006	Quadling et al.
7,166,063	B2	1/2007	Rahman et al.
7,184,150	B2	2/2007	Quadling et al.
7,192,273	B2	3/2007	McSurdy, Jr.
7,220,124	B2	5/2007	Taub et al.
7,286,954	B2	10/2007	Kopelman et al.
7,292,759	B2	11/2007	Boutoussov et al.
7,302,842	B2	12/2007	Biester et al.
7,338,327	B2	3/2008	Sticker et al.
D565,509	S	4/2008	Fechner et al.
7,351,116	B2	4/2008	Dold
7,357,637	B2	4/2008	Liechtung
7,450,231	B2	11/2008	Johs et al.
7,458,810	B2	12/2008	Bergersen
7,460,230	B2	12/2008	Johs et al.
7,462,076	B2	12/2008	Walter et al.
7,463,929	B2	12/2008	Simmons
7,500,851	B2	3/2009	Williams
D594,413	S	6/2009	Palka et al.
7,544,103	B2	6/2009	Walter et al.
7,553,157	B2	6/2009	Abolfathi et al.
7,561,273	B2	7/2009	Stautmeister et al.
7,577,284	B2	8/2009	Wong et al.
7,596,253	B2	9/2009	Wong et al.
7,597,594	B2	10/2009	Stadler et al.
7,609,875	B2	10/2009	Liu et al.
D603,796	S	11/2009	Sticker et al.
7,616,319	B1	11/2009	Woollam et al.
7,626,705	B2	12/2009	Altendorf
7,632,216	B2	12/2009	Rahman et al.
7,633,625	B1	12/2009	Woollam et al.
7,637,262	B2	12/2009	Bailey
7,668,355	B2	2/2010	Wong et al.
7,670,179	B2	3/2010	Muller
7,695,327	B2	4/2010	Bauerle et al.
7,698,068	B2	4/2010	Babayoff
7,724,378	B2	5/2010	Babayoff
D618,619	S	6/2010	Walter
7,731,508	B2	6/2010	Borst
7,735,217	B2	6/2010	Borst
7,780,460	B2	8/2010	Walter
7,787,132	B2	8/2010	Korner et al.
7,791,810	B2	9/2010	Powell
7,796,243	B2	9/2010	Choo-Smith et al.
7,806,727	B2	10/2010	Dold et al.
7,813,787	B2	10/2010	de Josselin de Jong et al.
7,824,180	B2	11/2010	Abolfathi et al.
7,828,601	B2	11/2010	Pyczak
7,845,969	B2	12/2010	Stadler et al.
7,854,609	B2	12/2010	Chen et al.
7,862,336	B2	1/2011	Kopelman et al.
7,872,760	B2	1/2011	Ertl
7,874,836	B2	1/2011	McSurdy, Jr.
7,874,849	B2	1/2011	Sticker et al.
7,878,801	B2	2/2011	Abolfathi et al.
7,907,280	B2	3/2011	Johs et al.
7,929,151	B2	4/2011	Liang et al.
7,947,508	B2	5/2011	Tricca et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,959,308 B2	6/2011	Freeman et al.
7,963,766 B2	6/2011	Cronauer
7,986,415 B2	7/2011	Thiel et al.
8,017,891 B2	9/2011	Nevin
8,026,916 B2	9/2011	Wen
8,027,709 B2	9/2011	Arnone et al.
8,054,556 B2	11/2011	Chen et al.
8,077,949 B2	12/2011	Liang et al.
8,083,556 B2	12/2011	Stadler et al.
D652,799 S	1/2012	Mueller
8,118,592 B2	2/2012	Tortorici
8,126,025 B2	2/2012	Takeda
8,144,954 B2	3/2012	Quadling et al.
8,160,334 B2	4/2012	Thiel et al.
8,201,560 B2	6/2012	Dembro
8,215,312 B2	7/2012	Garabadian et al.
8,240,018 B2	8/2012	Walter et al.
8,279,450 B2	10/2012	Oota et al.
8,292,617 B2	10/2012	Brandt et al.
8,294,657 B2	10/2012	Kim et al.
8,297,286 B2	10/2012	Smernoff
8,306,608 B2	11/2012	Mandelis et al.
8,310,683 B2	11/2012	Babayoff et al.
8,314,764 B2	11/2012	Kim et al.
8,332,015 B2	12/2012	Ertl
8,354,588 B2	1/2013	Sticker et al.
8,363,228 B2	1/2013	Babayoff
8,366,479 B2	2/2013	Borst et al.
8,465,280 B2	6/2013	Sachdeva et al.
8,477,320 B2	7/2013	Stock et al.
8,488,113 B2	7/2013	Thiel et al.
8,520,922 B2	8/2013	Wang et al.
8,520,925 B2	8/2013	Duret
8,556,625 B2	10/2013	Lovely
8,570,530 B2	10/2013	Liang
8,573,224 B2	11/2013	Thornton
8,577,212 B2	11/2013	Thiel
8,594,408 B2	11/2013	Alpern et al.
8,650,586 B2	2/2014	Lee et al.
8,675,706 B2	3/2014	Seurin et al.
8,723,029 B2	5/2014	Pyczak et al.
8,743,923 B2	6/2014	Geske et al.
8,767,270 B2	7/2014	Curry et al.
8,768,016 B2	7/2014	Pan et al.
8,771,149 B2	7/2014	Rahman et al.
8,839,476 B2	9/2014	Adachi
8,870,566 B2	10/2014	Bergersen
8,878,905 B2	11/2014	Fisker et al.
8,899,976 B2	12/2014	Chen et al.
8,936,463 B2	1/2015	Mason et al.
8,948,482 B2	2/2015	Levin
8,956,058 B2	2/2015	Rosch
8,992,216 B2	3/2015	Karazivan
9,022,792 B2	5/2015	Sticker et al.
9,039,418 B1	5/2015	Rubbert
9,084,535 B2	7/2015	Girkin et al.
9,108,338 B2	8/2015	Sirovskiy et al.
9,144,512 B2	9/2015	Wagner
9,192,305 B2	11/2015	Levin
9,204,952 B2	12/2015	Lampalzer
9,242,118 B2	1/2016	Brawn
9,261,358 B2	2/2016	Atiya et al.
9,299,192 B2	3/2016	Kopelman
9,336,336 B2	5/2016	Deichmann et al.
9,408,743 B1	8/2016	Wagner
9,433,476 B2	9/2016	Khardekar et al.
9,439,568 B2	9/2016	Atiya et al.
9,444,981 B2	9/2016	Bellis et al.
9,500,635 B2	11/2016	Islam
9,506,808 B2	11/2016	Jeon et al.
9,513,470 B1	12/2016	Weaver
9,545,331 B2	1/2017	Ingemarsson-Matzen
9,584,771 B2	2/2017	Mandelis et al.
9,675,430 B2	6/2017	Verker et al.
9,693,839 B2	7/2017	Atiya et al.
9,744,006 B2	8/2017	Ross
9,936,186 B2	4/2018	Jesenko et al.
2001/0038705 A1	11/2001	Rubbert et al.
2002/0010568 A1	1/2002	Rubbert et al.
2002/0015934 A1	2/2002	Rubbert et al.
2003/0009252 A1	1/2003	Pavlovskaia et al.
2003/0048540 A1	3/2003	Xie et al.
2003/0139834 A1	7/2003	Nikolskiy et al.
2003/0190575 A1	10/2003	Hilliard
2003/0207224 A1	11/2003	Lotte
2003/0224311 A1	12/2003	Cronauer
2004/0009449 A1	1/2004	Mah et al.
2004/0019262 A1	1/2004	Perelgut
2004/0058295 A1	3/2004	Bergersen
2004/0090638 A1	5/2004	Babayoff
2004/0094165 A1	5/2004	Cook
2005/0031196 A1	2/2005	Moghaddam et al.
2005/0037312 A1	2/2005	Uchida
2005/0048433 A1	3/2005	Hilliard
2005/0100333 A1	5/2005	Kerschbaumer et al.
2005/0181333 A1	8/2005	Karazivan et al.
2005/0186524 A1	8/2005	Abolfathi et al.
2005/0244781 A1	11/2005	Abels et al.
2006/0001739 A1	1/2006	Babayoff
2006/0084024 A1	4/2006	Farrell
2006/0099546 A1	5/2006	Bergersen
2006/0154198 A1	7/2006	Durbin et al.
2006/0223032 A1	10/2006	Fried et al.
2006/0223342 A1	10/2006	Borst et al.
2006/0234179 A1	10/2006	Wen et al.
2007/0046865 A1	3/2007	Umeda et al.
2007/0053048 A1	3/2007	Kumar et al.
2007/0087300 A1	4/2007	Willison et al.
2007/0184402 A1	8/2007	Boutoussov et al.
2007/0231765 A1	10/2007	Phan et al.
2007/0296959 A1	12/2007	Schwotzer
2008/0045053 A1	2/2008	Stadler et al.
2008/0062429 A1	3/2008	Liang et al.
2008/0063998 A1	3/2008	Liang et al.
2008/0090208 A1	4/2008	Rubbert
2008/0115791 A1	5/2008	Heine
2008/0176448 A1	7/2008	Muller et al.
2008/0242144 A1	10/2008	Dietz
2009/0030347 A1	1/2009	Cao
2009/0040740 A1	2/2009	Muller et al.
2009/0061379 A1	3/2009	Yamamoto et al.
2009/0061381 A1	3/2009	Durbin et al.
2009/0075228 A1	3/2009	Kumada et al.
2009/0210032 A1	8/2009	Beiski et al.
2009/0218514 A1	9/2009	Klunder et al.
2009/0298017 A1	12/2009	Boerjes et al.
2009/0305540 A1	12/2009	Stadler et al.
2010/0045902 A1	2/2010	Ikeda et al.
2010/0085636 A1	4/2010	Berner
2010/0152599 A1	6/2010	DuHamel et al.
2010/0165275 A1	7/2010	Tsukamoto et al.
2010/0167225 A1	7/2010	Kuo
2010/0231577 A1	9/2010	Kim et al.
2010/0312484 A1	12/2010	DuHamel et al.
2011/0045428 A1	2/2011	Boltunov et al.
2011/0081625 A1	4/2011	Fuh
2011/0102549 A1	5/2011	Takahashi
2011/0102566 A1	5/2011	Zakian et al.
2011/0143673 A1	6/2011	Landesman et al.
2011/0229840 A1	9/2011	Liang et al.
2011/0235045 A1	9/2011	Koerner et al.
2011/0269092 A1	11/2011	Kuo et al.
2012/0081786 A1	4/2012	Mizuyama et al.
2012/0086681 A1	4/2012	Kim et al.
2012/0092461 A1	4/2012	Fisker et al.
2012/0129117 A1	5/2012	McCance
2012/0147912 A1	6/2012	Moench et al.
2012/0172678 A1	7/2012	Logan et al.
2012/0281293 A1	11/2012	Gronenborn et al.
2012/0295216 A1	11/2012	Dykes et al.
2012/0322025 A1	12/2012	Ozawa et al.
2013/0089828 A1	4/2013	Borovinskih et al.
2013/0095446 A1	4/2013	Andreiko et al.
2013/0103176 A1	4/2013	Kopelman et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2013/0110469	A1	5/2013	Kopelman
2013/0163627	A1	6/2013	Seurin et al.
2013/0201488	A1	8/2013	Ishihara
2013/0235165	A1	9/2013	Gharib et al.
2013/0252195	A1	9/2013	Popat
2013/0266326	A1	10/2013	Joseph et al.
2013/0280671	A1	10/2013	Brawn et al.
2013/0286174	A1	10/2013	Urakabe
2013/0293824	A1	11/2013	Yoneyama et al.
2013/0323664	A1	12/2013	Parker
2013/0323671	A1	12/2013	Dillon et al.
2013/0323674	A1	12/2013	Hakomori et al.
2014/0081091	A1	3/2014	Abolfathi et al.
2014/0272774	A1	9/2014	Dillon et al.
2014/0294273	A1	10/2014	Jaisson
2014/0313299	A1	10/2014	Gebhardt et al.
2014/0329194	A1	11/2014	Sachdeva et al.
2014/0363778	A1	12/2014	Parker
2015/0002649	A1	1/2015	Nowak et al.
2015/0029309	A1	1/2015	Michaeli et al.
2015/0079531	A1	3/2015	Heine
2015/0140502	A1	5/2015	Brawn et al.
2015/0164335	A1	6/2015	Van Der Poel et al.
2015/0173856	A1	6/2015	Lowe et al.
2015/0230885	A1	8/2015	Wucher
2015/0238280	A1	8/2015	Wu et al.
2015/0238283	A1	8/2015	Tanugula et al.
2015/0306486	A1	10/2015	Logan et al.
2015/0320320	A1	11/2015	Kopelman et al.
2015/0325044	A1	11/2015	Lebovitz
2015/0338209	A1	11/2015	Knuttel
2016/0000332	A1	1/2016	Atiya et al.
2016/0003610	A1	1/2016	Lampert et al.
2016/0045291	A1	2/2016	Verker et al.
2016/0051345	A1	2/2016	Levin
2016/0064898	A1	3/2016	Atiya et al.
2016/0067013	A1	3/2016	Morton et al.
2016/0081768	A1	3/2016	Kopelman et al.
2016/0081769	A1	3/2016	Kimura et al.
2016/0135924	A1	5/2016	Choi et al.
2016/0135925	A1	5/2016	Mason et al.
2016/0163115	A1	6/2016	Furst
2016/0217708	A1	7/2016	Levin et al.
2016/0296303	A1	10/2016	Parker
2016/0328843	A1	11/2016	Graham et al.
2016/0330355	A1	11/2016	Tchouprakov et al.
2017/0007366	A1	1/2017	Kopelman et al.
2017/0007367	A1	1/2017	Li et al.
2017/0049311	A1	2/2017	Borovinskih et al.
2017/0049326	A1	2/2017	Alfano et al.
2017/0056131	A1	3/2017	Alauddin et al.
2017/0156821	A1	6/2017	Kopelman et al.
2017/0265970	A1	9/2017	Verker et al.
2017/0325690	A1	11/2017	Salah et al.
2018/0000563	A1	1/2018	Shanjani et al.
2018/0000565	A1	1/2018	Shanjani et al.
2018/0028063	A1	2/2018	Elbaz et al.
2018/0028064	A1	2/2018	Elbaz et al.
2018/0028065	A1	2/2018	Elbaz et al.
2018/0055602	A1	3/2018	Kopelman et al.
2018/0125610	A1	5/2018	Carrier, Jr. et al.
2018/0153648	A1	6/2018	Shanjani et al.
2018/0153649	A1	6/2018	Wu et al.
2018/0153733	A1	6/2018	Kuo
2018/0280118	A1	10/2018	Cramer
2018/0284727	A1	10/2018	Cramer et al.

FOREIGN PATENT DOCUMENTS

AU	9150082	A	6/1984
AU	5598894	A	6/1994
CA	1121955	A1	4/1982
CN	102802520	A	11/2012
DE	2749802	A1	5/1978
DE	69327661	T2	7/2000
DE	102005043627	A1	3/2007
DE	202010017014	U1	3/2011
DE	102011051443	A1	1/2013
DE	102014225457	A1	6/2016
EP	0428152	A1	5/1991
EP	490848	A2	6/1992
EP	541500	A1	5/1993
EP	0714632	B1	5/1997
EP	774933	B1	12/2000
EP	731673	B1	5/2001
EP	1941843	A2	7/2008
EP	2213223	A1	8/2010
EP	2437027	A2	4/2012
EP	2447754	A1	5/2012
EP	1989764	B1	7/2012
EP	2332221	B1	11/2012
EP	2596553	B1	12/2013
EP	2612300	B1	2/2015
EP	2848229	A1	3/2015
ES	463897	A1	1/1980
ES	2455066	A1	4/2014
FR	2369828	A1	6/1978
FR	2930334	A1	10/2009
GB	1550777	A	8/1979
JP	H53-058191	A	5/1978
JP	04-028359	A	1/1992
JP	H08-508174	A	9/1996
JP	63-11148		1/1998
JP	2002-522752	A	7/2002
JP	2003290133	A	10/2003
JP	2007-260158	A	10/2007
JP	2008-523370	A	7/2008
JP	04184427	B1	11/2008
JP	2009-000412	A	1/2009
JP	2009-018173	A	1/2009
JP	2011-087733	A	5/2011
JP	2012-526977	A	11/2012
JP	2013-007645	A	1/2013
JP	2016528972	A	9/2016
KR	10-1266966	B1	5/2013
KR	10-2016-041632	A	4/2016
KR	10-2016-0071127	A	6/2016
WO	91-004713	A1	4/1991
WO	94-010935	A1	5/1994
WO	98-032394	A1	7/1998
WO	98-044865	A1	10/1998
WO	2000/08415	A1	2/2000
WO	2002-017776	A2	3/2002
WO	2002-062252	A1	8/2002
WO	2002-095475	A1	11/2002
WO	2003-003932	A2	1/2003
WO	2006-096558	A2	9/2006
WO	2006-133548	A1	12/2006
WO	2009-085752	A2	7/2009
WO	2009-089129	A1	7/2009
WO	2009-146788	A1	12/2009
WO	2009-146789	A1	12/2009
WO	2012-007003	A1	1/2012
WO	2012-064684	A2	5/2012
WO	2012-074304	A2	6/2012
WO	2014-091865	A1	6/2014
WO	2015/015289	A2	2/2015
WO	2015-015289	A2	2/2015
WO	2015-063032	A1	5/2015
WO	2015-176004	A1	11/2015
WO	2016-004415	A1	1/2016
WO	2016-042393	A1	3/2016
WO	2016-061279	A1	4/2016
WO	2016-084066	A1	6/2016
WO	2016-099471	A1	6/2016
WO	2016-113745	A1	7/2016

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

WO	2016-116874 A1	7/2016
WO	2018-085718 A2	5/2018

OTHER PUBLICATIONS

Kochanek et al., "Interpolating Splines with Local Tension, Continuity and Bias Control", Computer Graphics; 18(3); pp. 33-41; Jan. 1, 1984.

Kumar et al.; Rapid maxillary expansion: A unique treatment modality in dentistry; J. Clin. Diagn. Res.; 5(4); pp. 906-911; Aug. 2011.

Kunii et al., "Articulation Simulation for an Intelligent Dental Care System" Displays; 15(3); pp. 181-188; Jul. 1994.

Kuroda et al., "Three-Dimensional Dental Cast Analyzing System Using Laser Scanning", American Journal of Orthodontics and Dentofacial Orthopedics; 11 0(4); pp. 365-369; Oct. 1996.

Laurendeau et al., "A Computer-Vision Technique for the Acquisition and Processing of 3-D Profiles of Dental Imprints: An Application in Orthodontics", IEEE Transactions on Medical Imaging; 1 0(3); pp. 453-461; Sep. 1991.

Leinfelder et al., "A New Method for Generating Ceramic Restorations: a CAD-CAM System" Journal of the American Dental Association; 118(6); pp. 703-707; Jun. 1989.

Manetti et al., "Computer-Aided Cefalometry and New Mechanics in Orthodontics" Fortschr Kieferorthop; 44; pp. 370-376; 8 pages; (English Article Summary Included); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1983.

McCann; Inside the ADA; J. Amer. Dent. Assoc, 118:286-294; Mar. 1989.

McNamara et al., "Invisible Retainers", J. Clin Orthod.; pp. 570-578; 11 pages; (Author Manuscript); Aug. 1985.

McNamara et al.; "Orthodontic and Orthopedic Treatment in the Mixed Dentition", Needham Press; pp. 347-353; Jan. 1993.

Moermann et al, "Computer Machined Adhesive Porcelain Inlays: Margin Adaptation after Fatigue Stress", IADR Abstract 339; J. Dent. Res.; 66(a):763; (Abstract Only); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1987.

Moles, "Correcting Mild Malalignments—As Easy As One, Two, Three", AOA/Pro Corner; 11 (2); 2 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2002.

Mormann et al.; "Marginale Adaptation von adhasuven Porzellaninlays in vitro", Separatdruck aus:Schweiz. Mschr. Zahnmed.; 95; pp. 1118-1129: 8 pages; (Machine Translated English Abstract); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 1985.

Nahoum, "The Vacuum Formed Dental Contour Appliance", N.Y. State Dent. J.; 30(9); pp. 385-390; Nov. 1964.

Nash, "CEREC CAD/CAM Inlays: Aesthetics and Durability in a Single Appointment", Dentistry Today; 9(8); pp. 20, 22-23 and 54; Oct. 1990.

Nedelcu et al.; "Scanning Accuracy and Precision in 4 Intraoral Scanners: An In Vitro Comparison Based on 3-Dimensional Analysis"; J. Prosthet. Dent.; 112(6); pp. 1461-1471; Dec. 2014.

Nishiyama et al., "A New Construction of Tooth Repositioner by LTV Vinyl Silicone Rubber", Journal of Nihon University School of Dentistry; 19(2); pp. 93-102 (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1977.

Ogawa et al., "Mapping, profiling and clustering of pressure pain threshold (PPT) in edentulous oral muscosa", Journal of Dentistry; 32(3); pp. 219-228; Mar. 2004.

Ogimoto et al., "Pressure-pain threshold determination in the oral mucosa: validity and reliability", Journal of Oral Rehabilitation; 29(7); pp. 620-626; Jul. 2002.

Paul et al.; "Digital Documentation of Individual Human Jaw and Tooth Forms for Applications in Orthodontics; Oral Surgery and Forensic Medicine" Proc. of the 24th Annual Conf. of the IEEE Industrial Electronics Society (IECON '98); vol. 4; pp. 2415-2418; Sep. 4, 1998.

Pinkham, "'Foolish' Concept Propels Technology", Dentist, 3 pages, Jan./Feb. 1989.

Pinkham, "Inventor's CAD/CAM May Transform Dentistry", Dentist; pp. 1 and 35, Sep. 1990.

Ponitz, "Invisible Retainers", American Journal of Orthodics, 59(3); pp. 266-272; Mar. 1971.

Procera Research Projects; Procera Research Projects 1993. Abstract Collection; 23 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1993.

Proffit et al., "The First Stage of Comprehensive Treatment: Alignment and Leveling", Contemporary Orthodontics, 3rd Ed.; Chapter 16; Mosby Inc.; pp. 534-537; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2000.

Proffit et al.; "The First Stage of Comprehensive Treatment: Alignment and Leveling", Contemporary Orthodontics; (Second Ed.); Chapter 15, MosbyYear Book; St. Louis, Missouri; pp. 470-533 Oct. 1993.

Raintree Essix & Ars Materials, Inc., Raintree Essix, Technical Magazine Table of contents and Essix Appliances, 7 pages; retrieved from the internet (http:llwww.essix.comlmagazineldefaulthtml) on Aug. 13, 1997.

Redmond et al.; "Clinical Implications of Digital Orthodontics", American Journal of Orthodontics and Dentofacial Orthopedics; 117(2); pp. 240-242; Feb. 2000.

Rekow et al., "CAD/CAM for Dental Restorations—Some of the Curious Challenges", IEEE Transactions on Biomedical Engineering; 38(4); pp. 314-318; Apr. 1991.

Rekow et al., "Comparison of Three Data Acquisition Techniques for 3-D Tooth Surface Mapping", Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 13(1); pp. 344-345 (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1991.

Rekow, "A Review of the Developments in Dental CAD/CAM Systems", Current Opinion in Dentistry; pp. 25-33; Jun. 1992.

Rekow, "CAD/CAM in Dentistry: A Historical Perspective and View of the Future", Journal Canadian Dental Association; 58(4); pp. 283, 287-288; Apr. 1992.

Rekow, "Computer-Aided Design and Manufacturing in Dentistry: A Review of the State of the Art", Journal of Prosthetic Dentistry; 58(4); pp. 512-516; Dec. 1987.

Rekow, "Dental CAD-CAM Systems: What is the State of the Art?", The Journal of the American Dental Association; 122(12); pp. 43-48; Dec. 1991.

Rekow, "Feasibility of an Automated System for Production of Dental Restorations", Ph.D. Thesis; Univ. of Minnesota, 250 pages, Nov. 1988.

Richmond et al., "The Development of a 3D Cast Analysis System", British Journal of Orthodontics; 13(1); pp. 53-54; Jan. 1986.

Richmond et al., "The Development of the PAR Index (Peer Assessment Rating): Reliability and Validity", The European Journal of Orthodontics; 41(2); pp. 125-139; Apr. 1992.

Richmond, "Recording the Dental Cast in Three Dimensions", American Journal of Orthodontics and Dentofacial Orthopedics; 92(3); pp. 199-206; Sep. 1987.

Budge, "Dental Arch Analysis: Arch Form, A Review of the Literature" European Journal of Orthodontics; 3(4); pp. 279-284; Jan. 1981.

Sahm et al, "Micro-Electronic Monitoring of Functional Appliance Wear"; Eur J Orthod.; 12(3); pp. 297-301; Aug. 1990.

Sahm, "Presentation of a wear timer for the clarification of scientific questions in orthodontic orthopedics", Fortschritte der Kieferorthopadie; 51 (4); pp. 243-247; (Translation Included) Jul. 1990.

Sakuda et al. "Integrated Information-Processing System in Clinical Orthodontics: An Approach with Use of a Computer Network System", American Journal of Orthodontics and Dentofacial Orthopedics; 101 (3); pp. 210-220; 20 pages; (Author Manuscript) Mar. 1992.

(56) **References Cited**

OTHER PUBLICATIONS

Schafer et al.; "Quantifying patient adherence during active orthodontic treatment with removable appliances using microelectronic wear-time documentation"; Eur J Orthod.; 37(1) pp. 1-8; doi:10.1093/ejo/cju012; Jul. 3, 2014.
Schellhas et al., "Three-Dimensional Computed Tomography in Maxillofacial Surgical Planning", Archives of Otolaryngology—Head and Neck Surgery; 114(4); pp. 438-442; Apr. 1988.
Schroeder et al; Eds. "The Visual Toolkit", Prentice Hall PTR, New Jersey; Chapters 6, 8 & 9, (pp. 153-210,309-354, and 355-428; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1998.
Shilliday, "Minimizing finishing problems with the mini-positioner", American Journal of Orthodontics; 59(6); pp. 596-599; Jun. 1971.
Shimada et al.; Application of Optical Coherence Tomography (OCT) for Diagnosis of Caries, Cracks, and Defects of Restorations, Current Oral Health Reports; 2(2); pp. 73-80; Jun. 2015.
Chishti et al.; U.S. Appl. No. 60/050,342 entitled "Procedure for Moving Teeth Using a Seires of Retainers," filed Jun. 20, 1997.
Cottingham, "Gnathologic Clear Plastic Positioner", American Journal of Orthodontics; 55(1); pp. 23-31; Jan. 1969.
Crawford; CAD/CAM in the Dental Office: Does It Work?; Canadian Dental Journal; 57(2); pp. 121-123 Feb. 1991.
Crawford, Computers in Dentistry: Part 1: CAD/CAM: The Computer Moves Chairside, Part 2: F. Duret—A Man With a Vision, Part 3: The Computer Gives New Vision—Literally, Part 4: Bytes 'N Bites the Computer Moves From the Front Desk to the Operatory; Canadian Dental Journal; 54(9); pp. 661-666 Sep. 1988.
Crooks; CAD/CAM Comes to USC; USC Dentistry; pp. 14-17; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) Spring 1990.
Cureton, "Correcting Malaligned Mandibular Incisors with Removable Retainers", Journal of Clinical Orthodontics; 30(7); pp. 390-395; Jul. 1996.
Curry et al., "Integrated Three-Dimensional Craniofacial Mapping at the Craniofacial Research Instrumentation Laboratory / University of the Pacific", Seminars in Orthodontics; 7(4); pp. 258-265; Dec. 2001.
Cutting et al., "Three-Dimensional Computer-Assisted Design of Craniofacial Surgical Procedures: Optimization and Interaction with Cephalometric and CT-Based Models", Plastic and Reconstructive Surgery; 77(6); pp. 877-885; Jun. 1986.
DCS Dental AG; The CAD/CAM 'DCS Titan System' for Production of Crowns/Bridges; DSC Production; pp. 1-7; Jan. 1992.
Defranco et al., "Three-Dimensional Large Displacement Analysis of Orthodontic Appliances", Journal of Biomechanics; 9(12); pp. 793-801; Jan. 1976.
Dental Institute University of Zurich Switzerland; Program for International Symposium on Computer Restorations: State of the Art of the CEREC-Method; 2 pages; May 1991.
Dentrac Corporation; Dentrac document; pp. 4-13; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1992.
Dent-x; "DentSim . . . Dent-x's virtual reality 3-D training simulator . . . A revolution in dental education", 6 pages; retrieved from the Internet (http://www.dent-x.com/DentSim.htm); on Sep. 24, 1998.
Doruk et al., "The role of the headgear timer in extraoral co-operation", European Journal of Orthodontics; 26; pp. 289-291; Jun. 1, 2014.
Doyle; "Digital Dentistry, Doctors use CAD/CAM to take the pain out of extensive dental procedures", Computer Graphics World; pp. 50-52 and p. 54; Oct. 2000.
Dummer et al., "Computed Radiography Imaging Based on High-Density 670 nm VCSEL Arrays", International Society for Optics and Photonics; vol. 7557, p. 7557OH, 7 pages; (Author Manuscript); Feb. 24, 2010.
Duret et al., "CAD/CAM Imaging in Dentistry", Current Opinion in Dentistry; 1 (2); pp. 150-154; Apr. 1991.
Duret et al; CAD-CAM in Dentistry; Journal of the American Dental Association; 117(6); pp. 715-720; Nov. 1988.
Duret, "The Dental CAD/CAM, General Description of the Project", Hennson International Product Brochure, 18 pages; Jan. 1986.
Duret; Vers Une Prosthese Informatisee; Tonus; 75(15); pp. 55-57; (English translation attached); 23 pages; Nov. 15, 1985.
Economides, "The Microcomputer in the Orthodontic Office", Journal of Clinical Orthodontics; 13(11); pp. 767-772; Nov. 1979.
Elsasser, "Some Observations on the History and Uses of the Kesling Positioner", American Journal of Orthodontics; 36(5); pp. 368-374; May 1, 1950.
Faber et al., "Computerized Interactive Orthodontic Treatment Planning", American Journal of Orthodontics; 73(1); pp. 36-46; Jan. 1978.
Felton et al., "A Computerized Analysis of the Shape and Stability of Mandibular Arch Form", American Journal of Orthodontics and Detofacial Orthopedics, Dec. 1987, pp. 478-483, vol. 92 No. 6, The C. V. Mosby Company.
Friede et al., "Accuracy of Cephalometric Prediction in Orthognathic Surgery", Journal of Oral and Maxillofacial Surgery; 45(9); pp. 754-760; Sep. 1987.
Friedrich et al; "Measuring system for in vivo recording of force systems in orthodontic treatment—concept and analysis of accuracy", J. Biomech.; 32(1); pp. 81-85; (Abstract only) Jan. 1999.
Futterling et al, "Automated Finite Element Modeling of a Human Mandible with Dental Implants", JS WSCG '98—Conference Program; 8 pages; retrieved from the Internet (https://dspace5.zcu.cz/bitstream/11025/15851/1/Strasser_98.pdf); on Aug. 21, 2018.
Gao et al., "3-D Element Generation for Multi-Connected Complex Dental and Mandibular Structure", IEEE Proceedings International Workshop in Medical Imaging and Augmented Reality; pp. 267-271; Jun. 12, 2001.
Gim-Alldent Deutschland, "Das DUX System: Die Technik," 3 pages; (English Translation Included); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 2002.
Gottleib et al., JCO Interviews Dr. James A. McNamura, Jr., on the Frankel Appliance: Part 2: Clinical Management:, Journal of Clinical Orthodontics; 16(6), Jun. 1982, pp. 390-407; retrieved from the internet (http://www .ico-online.com/archive/print_article.asp?Year=1982&Month=06&ArticleNum+) on Mar. 9, 2005.
Grayson, "New Methods for Three Dimensional Analysis of Craniofacial Deformity", Symposium: Computerized Facial Imaging in Oral and Maxillofacial Surgery; American Association of Oral and Maxillofacial Surgeons; 48(8) suppl 1; pp. 5-6; Sep. 13, 1990.
Grest, Daniel, Marker-Free Human Motion Capture in Dynamic Cluttered Environments from a Single View-Point:, PhD Thesis; 167 pages; Dec. 2007, Kiel, Germany.
Guess et al. "Computer Treatment Estimates in Orthodontics and Orthognathic Surgery" Journal of Clinical Orthodontics; 23(4); pp. 262-268; 11 pages; (Author Manuscript); Apr. 1989.
Heaven et al.; Computer-Based Image Analysis of Artificial Root Surface Caries; Abstracts of Papers #2094; Journal of Dental Research; vol. 70, Special Issue; p. 528; (Abstract Only); Apr. 17-21, 1991.
Highbeam Research, "Simulating stress put on jaw. (ANSYS Inc.'s finite element analysis software)" Nov. 1, 1996, 2 pages; retrieved from the Internet (http://static.highbeam.eom/titoolingampproduction/november011996/simulatingstressputonfa . . .); on Nov. 5, 2004.
Hikage, "Integrated Orthodontic Management System for Virtual Three-Dimensional Computer Graphic Simulation and Optical Video Image Database for Diagnosis and Treatment Planning" Journal of Japan KA Orthodontic Society; 46(2); pp. 248-269; 56 pages; (English Translation Included); Feb. 26, 1987.
Hoffmann et al., "Role of Cephalometry for Planning of Jaw Orthopedics and Jaw Surgery Procedures", Informatbnen, pp. 375-396; (English Abstract Included); Mar. 1991.
Hojjatie et al., Three-Dimensional Finite Element Analysis of Glass-Ceramic Dental Crowns; Journal of Biomechanics; 23(11); pp. 1157-1166; Jan. 1990.

(56) **References Cited**

OTHER PUBLICATIONS

Huckins, "CAD-CAM Generated Mandibular Model Prototype from MRI Data", AAOMS, p. 96; (Abstract Only); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1999.
Invisalign; "You were made to move. There's never been a better time to straighten your teeth with the most advanced clear aligner in the world"; Product webpage; 2 pages; retrieved from the internet (www.invisalign.com/) on Dec. 28, 2017.
JCO Interviews, "Craig Andreiko , DDS, MS on the Elan and Orthos Systems; Interview by Dr. Larry W. White", Journal of Clinical Orthodontics; 28(8); pp. 459-468; 14 pages; (Author Manuscript); Aug. 1994.
JCO Interviews; "Dr. Horner W. Phillips on Computers in Orthodontic Practice, Part 2", Journal of Clinical Orthodontics; 17(12); pp. 819-831; 19 pages; Dec. 1983.
Jerrold, "The Problem, Electronic Data Transmission and the Law", American Journal of Orthodontics and Dentofacial Orthopedics; 113(4); 5 pages; (Author Manuscript); Apr. 1998.
Jones et al.; An Assessment of the Fit of a Parabolic Curve to Pre- and Post-Treatment Dental Arches; British Journal of Orthodontics; 16(2); pp. 85-93; May 1989.
Kamada et al., "Case reports on Tooth Positioners Using LTV Vinyl Silicone Rubber", J. Nihon University School of Dentistry; 26(1); pp. 11-29; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1984.
Kamada et al. "Construction of Tooth Positioners with OTV Vinyl Silicone Rubber and Some Case Reports", J. Nihon University School of Dentistry; 24(1); pp. 1-27; (year of pub. Sufficiently earlier than effective US filing date anda ny foreign priority date) 1982.
Kanazawa et al., "Three-Dimensional Measurements of the Occlusal Surfaces of Upper Molars in a Dutch Population", Journal of Dental Research; 63(11); pp. 1298-1301; Nov. 1984.
Kesling et al., "The Philosophy of the Tooth Positioning Appliance", American Journal of Orthodontics and Oral Surgery; 31 (6); pp. 297-304; Jun. 1945.
Kesling, "Coordinating the Predetermined Pattern and Tooth Positioner with Conventional Treatment", American Journal of Orthodontics and Oral Surgery; 32(5); pp. 285-293; May 1946.
International Search Report and Written Opinion for PCT Application No. PCT/IB2015/054950 dated Apr. 1, 2016.
International Preliminary Report on Patentability and Written Opinion for International Application No. PCT/IB2015/054950 dated Jan. 10, 2017.
IP Australia, Examination Report No. 1 for Patent Application No. 2015287312 dated Jul. 31, 2017, 4 pages.2018, 5 pages.
IP Australia, Examination Report No. 2 for Patent Application No. 2015287312 dated Feb. 12, 2018, 4 pages.2018, 4 pages.
Canadian Intellectual Property Office, Office Action for Canadian Patent Application No. 2,949,448 dated Sep. 26, 2017, 3 pages.
Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated May 29, 2018.
Korean Intellectual Property Office, Notification of Reason for Refusal for Korean Patent Application No. 10-2017-7003299 dated Nov. 14, 2017, including English translation, 15 pages.
International Search Report and Written Opinion for International Patent Application No. PCT/US2018/013321 dated Apr. 26, 2018, 16 pages.
AADR, American Association for Dental Research; Summary of Activities; Los Angeles, CA; p. 195; Mar. 20-23, 1980.
Alcaniz et al., "An Advanced System for the Simulation and Planning of Orthodontic Treatments" Visualization in Biomedical Computing, 4th Intl. Conf, VBC '96, Sep. 22-25, 1996, pp. 511-520, Springer-Verlag, Hamburg, Germany.
Alexander et al., "The DigiGraph Work Station Part 2 Clinical Management", J. Clin. Orthod., Jul. 1990, 12 pages.
Allesee Orthodontic Appliances: "Important Tip About Wearing the Red White & Blue Active Clear Retainer System", Allesee Orthodontic Appliances-Pro Lab; 1 page; (year of pub. Sufficiently earlier than effecitve US filing date and any foreign priroirty date); 1998.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (Patient Information); retrieved from the internet (http://ormco.com/aoa/appliancesservices/RWB/patients.html); 2 pages on May 19, 2003.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (product information for doctors); retrieved from the internet (http://ormco.com/aoa/appliancesservices/RWB/doctrohtml); 5 pages on May 19, 2003.
Allesee Orthodontic Appliances; The Choice is Clear: Red, White & Blue . . . the Simple, Affordable, No-Braces Treatment; (product information), 6 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 2003.
Allesee Orthodontic Appliances; The Red, White & Blue Way to Improve Your Smile; (information for patients), 2 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1992.
Allesee Orthodontic Appliances; You may be a candidate for this invisible no-braces treatment; product information for patients; 2 pages; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 2002.
Allesee Orthodontic Applicances: Dura ClearTM; Product information; 1 page; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date) 1997.
Altschuler et al., Analysis of 3-D Data for Comparative 3-D Serial Growth Pattern Studies of Oral-Facial Structures; IADR Abstracts, Program and Abstracts of Papers, 57th General Session, AIDR Annual Session, Mar. 29, 1979-Apr. 1, 1979, New Orleans Marriot; Journal of Dental Research; vol. 58, Special Issue A, p. 221; Jan. 1979.
Altschuler et al., Laser Electro-Optic System for Rapid Three-Dimensional (3D) Topographic Mapping of Surfaces; Optical Engineering; Dec. 1981, pp. 953-961, vol. 20(6).
Altschuler et al., "Measuring Surfaces Space-Coded by a Laser-Projected Dot Matrix" SPIE Imaging Applications for Automated Industrial Inspection and Assembly; Oct. 10, 1979, pp. 187-191, vol. 182.
Altschuler; 3D Mapping of Maxillo-Facial Prosthesis; AADR Abstract #607; 1 page, (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1980.
Andersson et al.; Clinical Results with Titanium Crowns Fabricated with Machine Duplication and Spark Erosion; Acta Odontologica Scandinavica; 47(5); pp. 279-286; Oct. 1989.
Andrews, "The Six Keys to Optimal Occlusion" Straight Wire, Chapter 3, L.A. Wells; pp. 13-24; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1989.
Barone et al., "Creation of 30 Multi-Body Orthodontic Models by Using Independent Imaging Sensors"; Sensors; 13(2); pp. 2033-2050; Feb. 5, 2013.
Bartles et al.; An Introduction to Splines for Use in Computer Graphics and Geometric Modeling; Morgan Kaufmann Publishers; pp. 422-425 Jan. 1, 1987.
Baumrind et al, "Mapping the Skull in 3-D," reprinted from J. Calif. Dent. Assoc, 48(2), 11 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) Fall Issue 1972, vol. 48, No. 2.
Baumrind et al., "A Stereophotogrammetric System for the Detection of Prosthesis Loosening in Total Hip Arthroplasty", NATO Symposium on Applications of Human Biostereometrics; SPIE; vol. 166; pp. 112-123; Jul. 9-13, 1978.
Baumrind, "A System for Crania facial Mapping Through the Integration of Data from Stereo X-Ray Films and Stereo Photographs", an invited paper submitted to the 1975 American Society of Photogram Symposium on Close-Range Photogram Systems; University of Illinois; pp. 142-166; Aug. 26-30, 1975.
Baumrind, "Integrated Three-Dimensional Craniofacial Mapping: Background, Principles, and Perspectives", Seminars in Orthodontics; 7(4); pp. 223-232; Dec. 2001.
Begole et al.; A Computer System for the Analysis of Dental Casts; The Angle Orthodontist; 51(3); pp. 252-258, Jul. 1981.

(56) **References Cited**

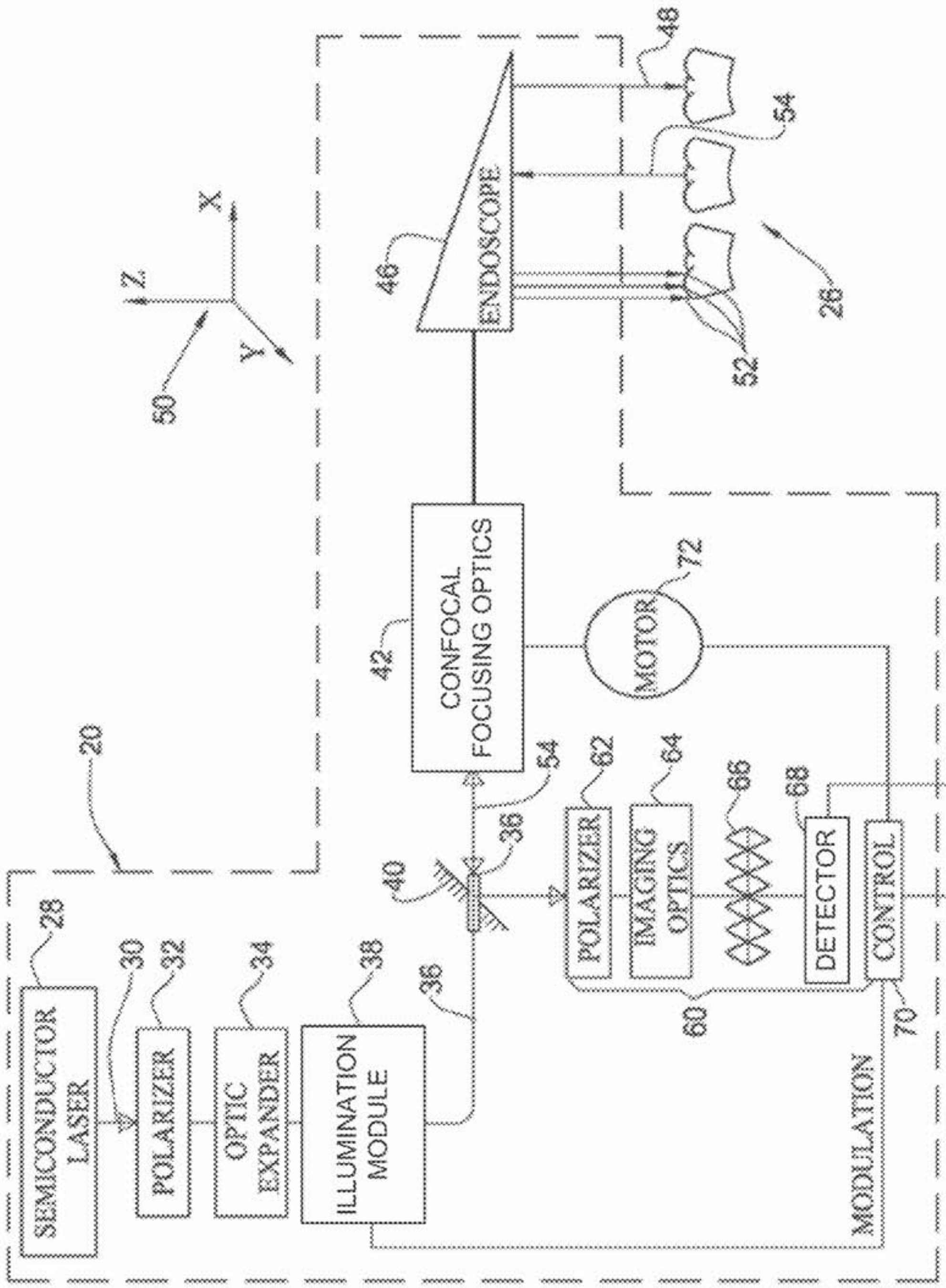
OTHER PUBLICATIONS

Bernard et al, "Computerized Diagnosis in Orthodontics for Epidemiological Studies: A ProgressReport" (Abstract Only), J. Dental Res. Special Issue, vol. 67, p. 169, paper presented at International Association for Dental Research 66th General Session, Montreal Canada; Mar. 9-13, 1988.
Bhatia et al., "A Computer-Aided Design for Orthognathic Surgery", British Journal of Oral and Maxillofacial Surgery; 22(4); pp. 237-253; Aug. 1, 1984.
Biggerstaff et al., "Computerized Analysis of Occlusion in the Postcanine Dentition", American Journal of Orthodontics; 61 (3); pp. 245-254; Mar. 1972.
Biggerstaff, "Computerized Diagnostic Setups and Simulations", Angle Orthodontist; 40(I); pp. 28-36; Jan. 1970.
Biostar Operation & Training Manual. Great Lakes Orthodontics, Ltd. 199 Fire Tower Drive, Tonawanda, New York. 14150-5890, 20 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1990.
Blu et al.; "Linear Interpolation Revitalized", IEEE Transactions on Image Processing; 13(5); pp. 710-719; May 2004.
Bourke, "Coordinate System Transformation", 2 pages, Jun. 1996, retrieved from the internet (http://local.wasp.uwa.edu.au/~pbourke/protection/coords/) on Sep. 19, 2006.
Boyd et al., "Three Dimensional Diagnosis and Orthodontic Treatment of Complex Malocclusions With the Invisalipn Appliance", Seminars in Orthodontics; 7(4); pp. 274-293; Dec. 2001.
Brandestini et al. "Computer Machined Ceramic Inlays: In Vitro Marginal Adaptation", J. Dent. Res. Special Issue; (Abstract 305); vol. 64; p. 208; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1985.
Brook et al., "An Image Analysis System for the Determination of Tooth Dimensions from Study Casts: Comparison with Manual Measurements of Mesio-distal Diameter", Journal of Dental Research; 65(3); pp. 428-431: Mar. 1986.
Burstone et al., "Precision Adjustment of the Transpalatal Lingual Arch: Computer Arch Form Predetermination", American Journal of Orthodontics; 79(2);pp. 115-133; Feb. 1981.
Burstone; "Dr. Charles J. Burstone on the Uses of the Computer in Orthodontic Practice (Part 1)"; Journal of Clinical Orthodontics; 13(7); pp. 442-453; (interview); Jul. 1979.
Burstone; "Dr. Charles J. Burstone on the Uses of the Computer in Orthodontic Practice (Part 2)"; Journal of Clinical Orthodontics; 13(8); pp. 539-551 (interview); Aug. 1979.
"Cardinal Industrial Finishes for Liquid and Powder Coatings", The Powder Coating Isntitute; 6 pages; retrieved from the internet (http://www.cardinalpaint.com/powder%20coatings.htm) on Aug. 25, 2000.
Carnaghan et al., "An Alternative to Holograms for the Portrayal of Human Teeth", 4th Int'l. Conf. on Holographic Systems, Components and Applications; pp. 228-231; Sep. 15, 1993.
Chaconas et al, "The DigiGraph Work Station, Part 1, Basic Concepts"; Journal of Clinical Orthodontics; 24(6); pp. 360-367; (Author Manuscript); Jun. 1990.
Chafetz et al., "Subsidence of the Femoral Prosthesis, A Stereophotogrammetric Evaluation", Clinical Orthopaedics and Related Research; No. 201; pp. 60-67; Dec. 1985.
Chiappone, "Constructing the Gnathologic Setup and Positioner", Journal of Clinical Orthodontics; 14(2); pp. 121-133; Feb. 1980.
Siemens; CEREC—"Computer-Reconstruction, High Tech in der Zahnmedizin", 15 pages; (Includes Machine Translation); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date); 2004.
Sinclair, "The Readers' Corner", Journal of Clinical Orthodontics; 26(6); pp. 369-372; 5 pages; retrived from the internet (http://www.jco-online.comlarchive/print_article .asp?Year= 1992&Month=06 &ArticleNum=); Jun. 1992.
Stoll et al.; "Computer-aided Technologies in Dentistry", Dtsch Zahna'rztl Z 45, pp. 314-322; (English Abstract Included); (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1990.
Sturman, "Interactive Keyframe Animation of 3-D Articulated Models", Proceedings Graphics Interface '84; vol. 86; pp. 35-40; May-Jun. 1984.
The American Heritage, Stedman's Medical Dictionary; "Gingiva"; 3 pages; retrieved from the interent (http://reference.com/search/search?q=gingiva) on Nov. 5, 2004.
The Dental Company Sirona, "Cerec Omnicam and Cerec Bluecam. The first choice in every case", product brochure, 8 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 2014.
Thera Mon; "Microsensor"; "2 pages"; retrieved from the Internet (www.english.thera-mon.com/the-product/transponder/index.html); on Sep. 19, 2016.
Thorlabs; Pellin broca prisms; 1 page; retrieved from the Internet (www.thorlabs.com); Nov. 30, 2012.
Truax, "Truax Clasp-Less(TM) Appliance System", The Functional Orthodontist; 9(5); pp. 22-24, 26-28; Sep.-Oct. 1992.
Tru-Tatn Orthodontic & Dental Supplies, Product Brochure, Rochester, Minnesota 55902, 16 pages; (year of pub. sufficiently earlier than effective US filing date and any foreign priority date) 1996.
U.S. Department of Commerce, National Technical Information Service, "Holodontography: An Introduction to Dental Laser Holography", School of Aerospace Medicine Brooks AFB Tex; Mar. 1973, 37 pages.
Schmidt, et al. "Automated Crown Replication Using Solid Photography SM", National Technical Information Service, Solid Photography Inc., Melville NY,; Oct. 1977; 19 pages.
Van Der Linden, "A New Method to Determine Tooth Positions and Dental Arch Dimensions", Journal fo Dental Research; 51(4); p. 1104; Jul.-Aug. 1972.
Van Der Linden et al, "Three-Dimensional Analysis of Dental Casts by Means of the Optocom", Journal of Dental Research; 51 (4); p. 11 00; Jul.-Aug. 1972.
Van Der Zel, "Ceramic-Fused-to-Metal Restorations with a New CAD/Cam System", Quintessence International; 24(A); pp. 769-778; (year of pub. Sufficiently earlier than effective US filing date and any foreign priority date); 1993.
Van Hilsen et al., "Comparing potential early caries assessment methods for teledentistry", BMC Oral Health; 13(16); doi: 10.1186/1472-6831-13-16; 9 pages; Mar. 2013.
Varady et al.; "Reverse Engineering of Geometric Models—An Introduction", Computer-Aided Design; 29(4); pp. 255-268; 29 pages; (Author Manuscript); May 13, 1996.
Verstreken et al., "An Image-Guided Planning System for Endosseous Oral Implants", IEEE Transactions on Medical Imaging; 17(5); pp. 842-852; Oct. 1998.
Warunek et al., "Physical and Mechanical Properties of Elastomers in Orthodonic Positioners", American Journal of Orthodontics and Dentofacial Orthopedics; 95(5); pp. 388-400; 21 pages; (Author Manuscript); May 1989.
Warunek et.al., "Clinical Use of Silicone Elastomer Applicances", JCO; 23 (10); pp. 694-700; Oct. 1989.
Wells, "Application of the Positioner Appliance in Orthodontic Treatment", American Journal of Orthodontics; 58(4); pp. 351-366; Oct. 1970.
Wishan, "New Advances in Personal Computer Applications for Cephalometric Analysis, Growth Prediction, Surgical Treatment Planning and Imaging Processing", Symposium: Computerized Facial Imaging in Oral and Maxilofacial Surgery; p. 5; Presented on Sep. 13, 1990.
Wikipedia; Palatal expansion; 3 pages; retrieved from the internet (https://en.wikipedia.org/wiki/Palatal_expansion) on Mar. 5, 2018.
Williams, "Dentistry and CAD/Cam: Another French Revolution", J. Dent. Practice Admin.; 4(1); pp. 2-5 Jan./Mar. 1987.
Williams, "The Switzerland and Minnesota Developments in CAD/CAM", Journal of Dental Practice Administration; 4(2); pp. 50-55; Apr./Jun. 1987.
Wireless Sensor Networks Magazine, "Embedded Teeth for Oral Activity Recognition", Jul. 29, 2013, 2 pages; retrieved on Sep. 19, 2016 from the internet (www.wsnmagazine.com/embedded-teeth/).
Witt et al., "The wear-timing measuring device in orthodontics-cui bono? Reflections on the state-of-the-art in wear-timing measure-

(56) **References Cited**

OTHER PUBLICATIONS

ment and compliance research in orthodontics"; Fortschr Kieferothop; 52(3); pp. 117-125; (Translation Included) Jun. 1991.
WSCG'98—Conference Program, The Sixth International Conference in Central Europe on Computer Graphics and Visualization '98; pp. 1-7; retrieved from the Internet on Nov. 5, 2004, (http://wscg.zcu.cz/wscg98/wscg98.htm); Feb. 9-13, 1998.
Xia et al., "Three-Dimensional Virtual-Reality Surgical Planning and Soft-Tissue Prediction for Orthognathic Surgery", IEEE Transactions on Information Technology in Biomedicine; 5(2); pp. 97-107; Jun. 2001.
Yamada et al., "Simulation of fan-beam type optical computer-tomography imaging of strongly scattering and weakly absorbing media", Applied Optics; 32(25); pp. 4808-4814; Sep. 1, 1993.
Yamamoto et al., "Optical Measurement of Dental Cast Profile and Application to Analysis of Three-Dimensional Tooth Movement in Orthodontics", Front. Med. Biol. Eng., 1(2); pp. 119-130; (year of pub. sufficiently earlier than affective US filing date and any foreign priority date); 1988.
Yamamoto et al., "Three-Dimensional Measurement of Dental Cast Profiles and Its Applications to Orthodontics", Conf. Proc. IEEE Eng. Med. Bioi. Soc.; 12(5); pp. 2052-2053; Nov. 1990.
Yamany et al., "A System for Human Jaw Modeling Using Intra-Oral Images", Proc. of the 20th Annual Conf. of the IEEE Engineering in Medicine and Biology Society; vol. 2; pp. 563-566; Oct. 1998.
Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); I. The D.P. Concept and Implementation of Transparent Silicone Resin (Orthocon)"; Nippon Dental Review; 452; pp. 61-74; 32 pages; (Author Manuscript); Jun. 1980.
Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); II. The D.P. Manufacturing Procedure and Clinical Applications", Nippon Dental Review; 454; pp. 107-130; 48 pages; (Author Manuscript); Aug. 1980.
Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.)—III. The General Concept of the D.P. Method and Its Therapeutic Effect, Part 1, Dental and Functional Reversed Occlusion Case Reports", Nippon Dental Review; 457; pp. 146-164; 43 pages; (Author Manuscript); Nov. 1980.
Yoshii, "Research on a New Orthodontic Appliance: The Dynamic Positioner (D.P.); III—The General Concept of the D.P. Method and Its Therapeutic Effect, Part 2. Skeletal Reversed Occlusion Case Reports", Nippon Dental Review; 458; pp. 112-129; 40 pages; (Author Manuscript); Dec. 1980.
Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated Dec. 18, 2018.
Park, H. et al. "Development of High Speed and High Accuracy 3D Dental Intra Oral Scanner," Procedia Eng. 100(2015) 1174-1181.
Third-Party Submission Under 37 CFR 1.290 for U.S. Appl. No. 15/859,010, filed Jan. 11, 2019.
International Search Report and Written Opinion for PCT Application No. PCT/IB2015/001400 dated Feb. 9, 2016, 18 pages.
Tiziani H. J. et al., "Confocal principle for macro- and microscopic surface and defect analysis," Optical Engineering, Jan. 1, 2000, pp. 32-39, vol. 39(1), Society of Photo-Optical Instrumentation Engineers.
Office Action for Chinese Patent Application No. 201580056255.2 dated Jan. 16, 2019,Chinese only, 7 pages.
Office Action for Chinese Patent Application No. 201580037043.X dated Jan. 2, 2019, with English translation, 18 pages.
Second Office Action for Chinese Patent Application No. 201580037043.X dated Jun. 19, 2019, with English translation, 22 pages.
Japanese Patent Office, Office Action for Japanese Patent Application No. JP 2017-500896 dated Jun. 11, 2019, with English translation, 6 pages.



SEMICONDUCTOR LASER
POLARIZER
OPTIC EXPANDER
ILLUMINATION MODULE
CONFOCAL FOCUSING OPTICS
ENDOSCOPE
MOTOR
POLARIZER
IMAGING OPTICS
DETECTOR
CONTROL
MODULATION
A
B
X
Y
Z
20
26
28
30
32
34
36
38
40
42
46
48
50
52
54
60
62
64
66
68
70
72

FIG. 1A

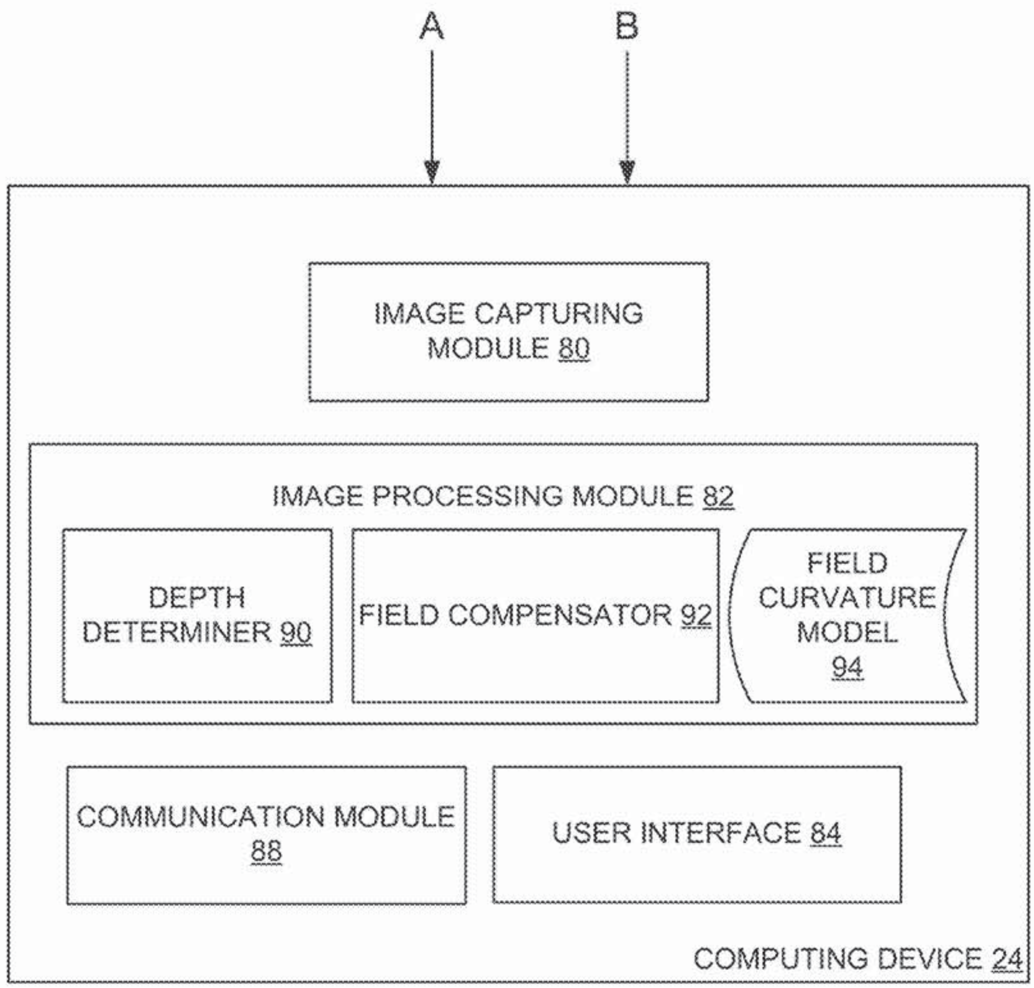

A
B
IMAGE CAPTURING MODULE 80
IMAGE PROCESSING MODULE 82
DEPTH DETERMINER 90
FIELD COMPENSATOR 92
FIELD CURVATURE MODEL 94
COMMUNICATION MODULE 88
USER INTERFACE 84
COMPUTING DEVICE 24

FIG. 1B

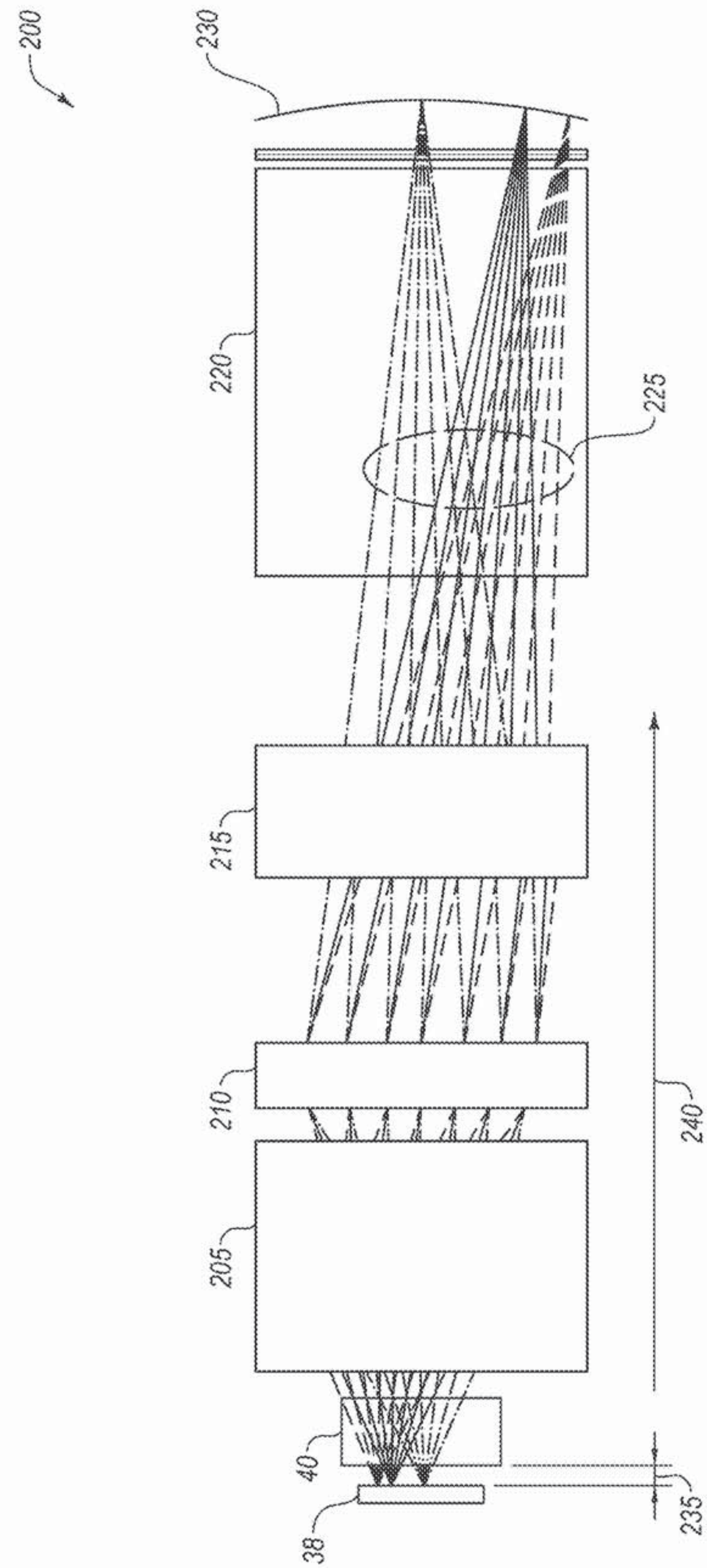


FIG. 2A

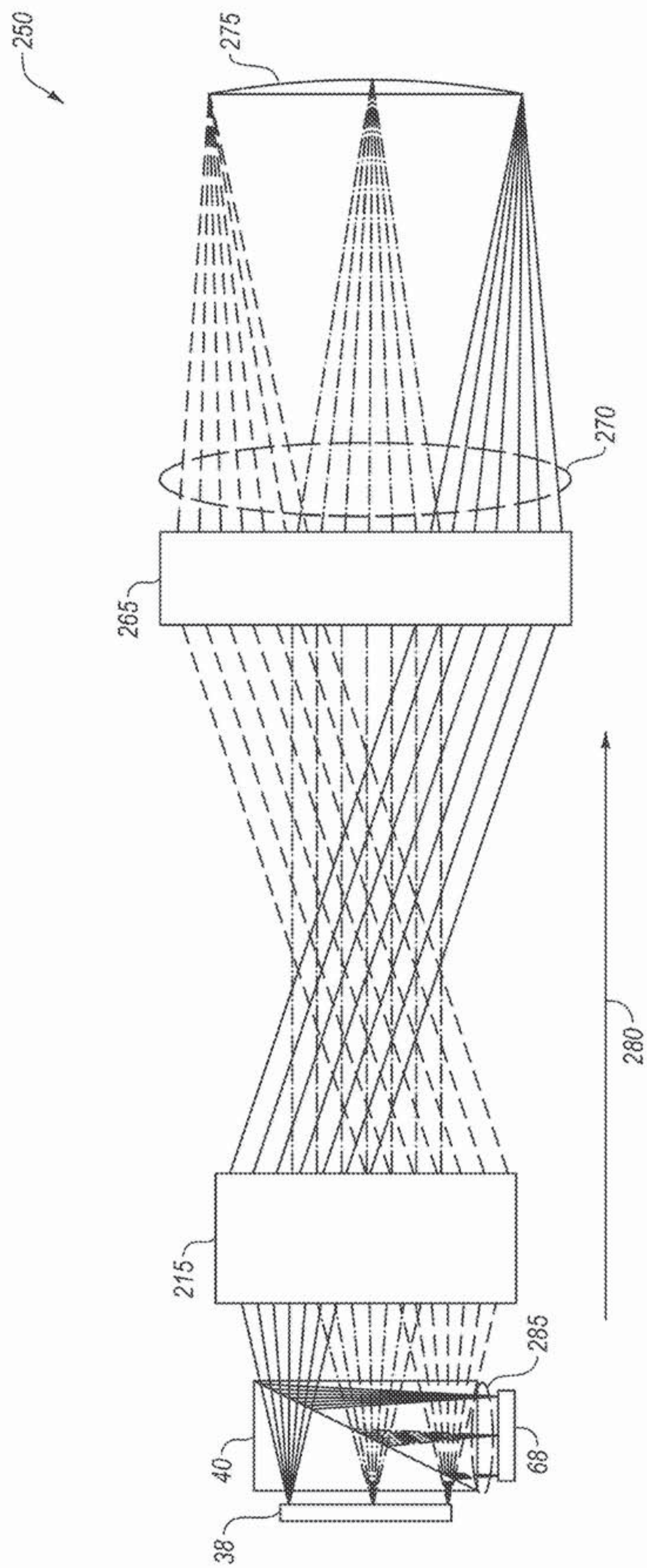


FIG. 2B

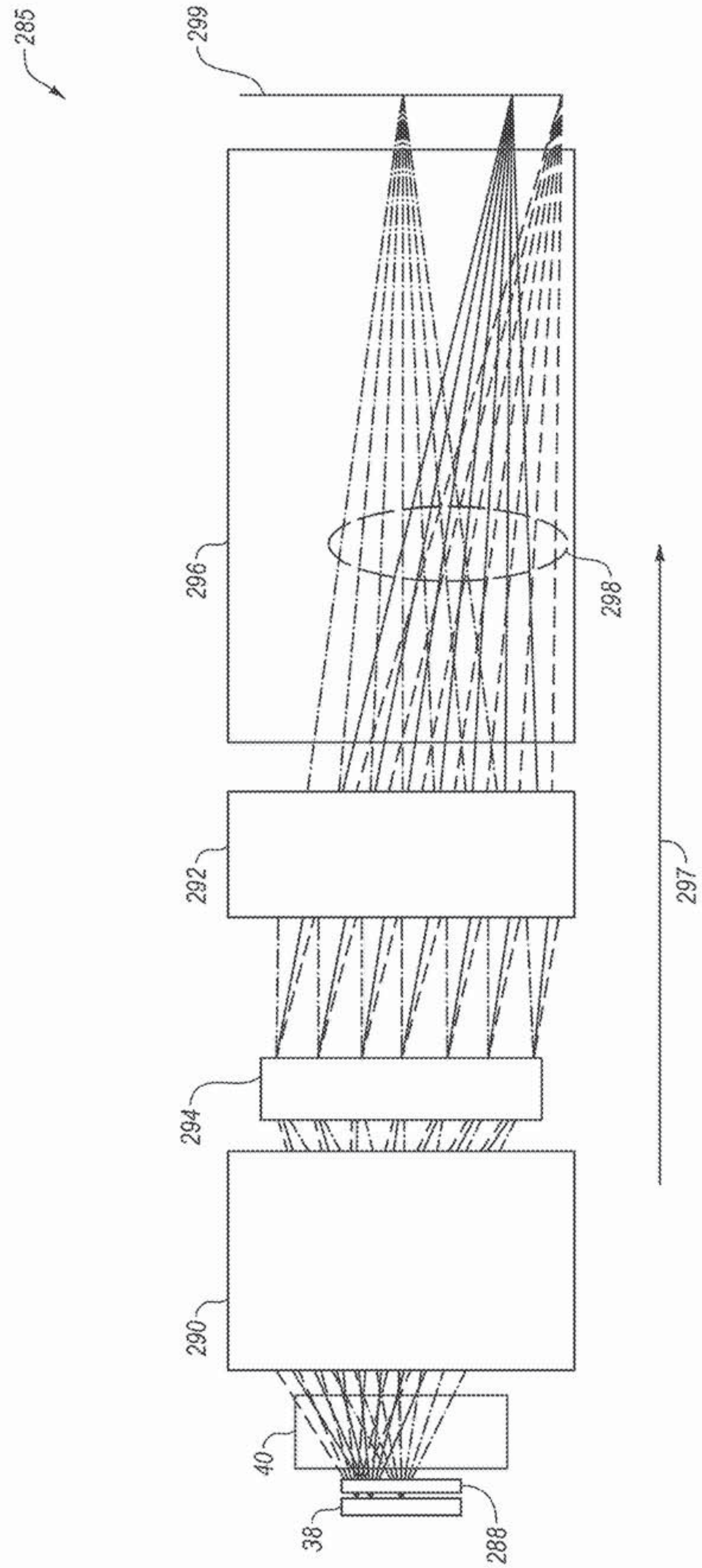
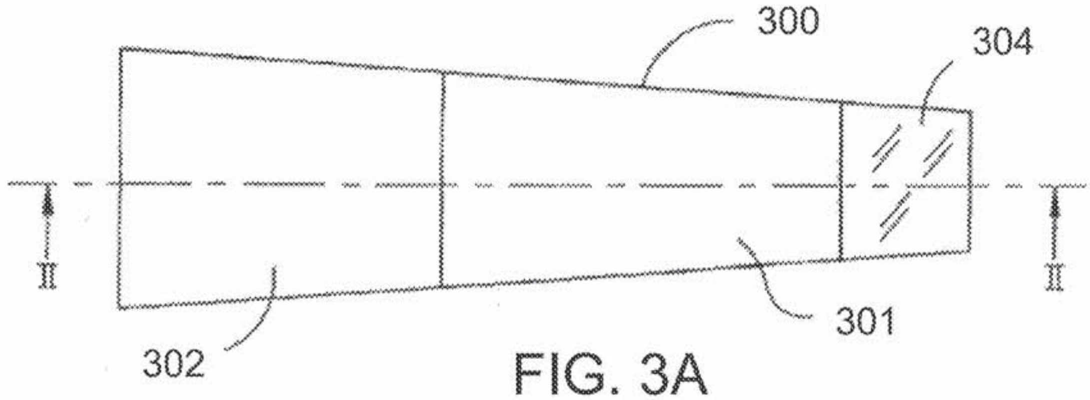
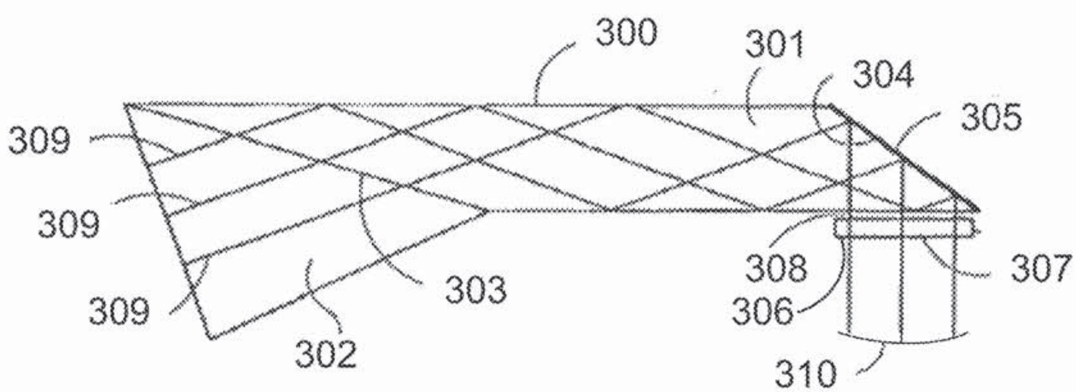


FIG. 2C



300
304
II
II
302
301

FIG. 3A



300
301
304
305
309
309
309
303
302
308
306
307
310

FIG. 3B

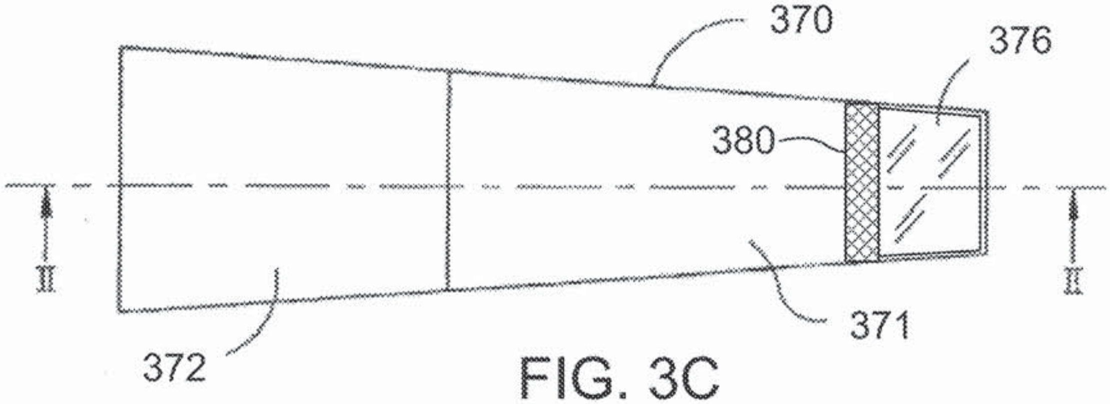


FIG. 3C

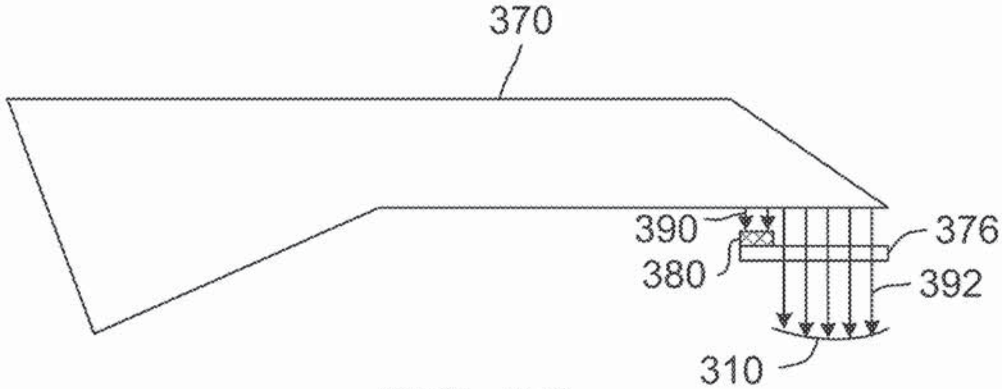


FIG. 3D

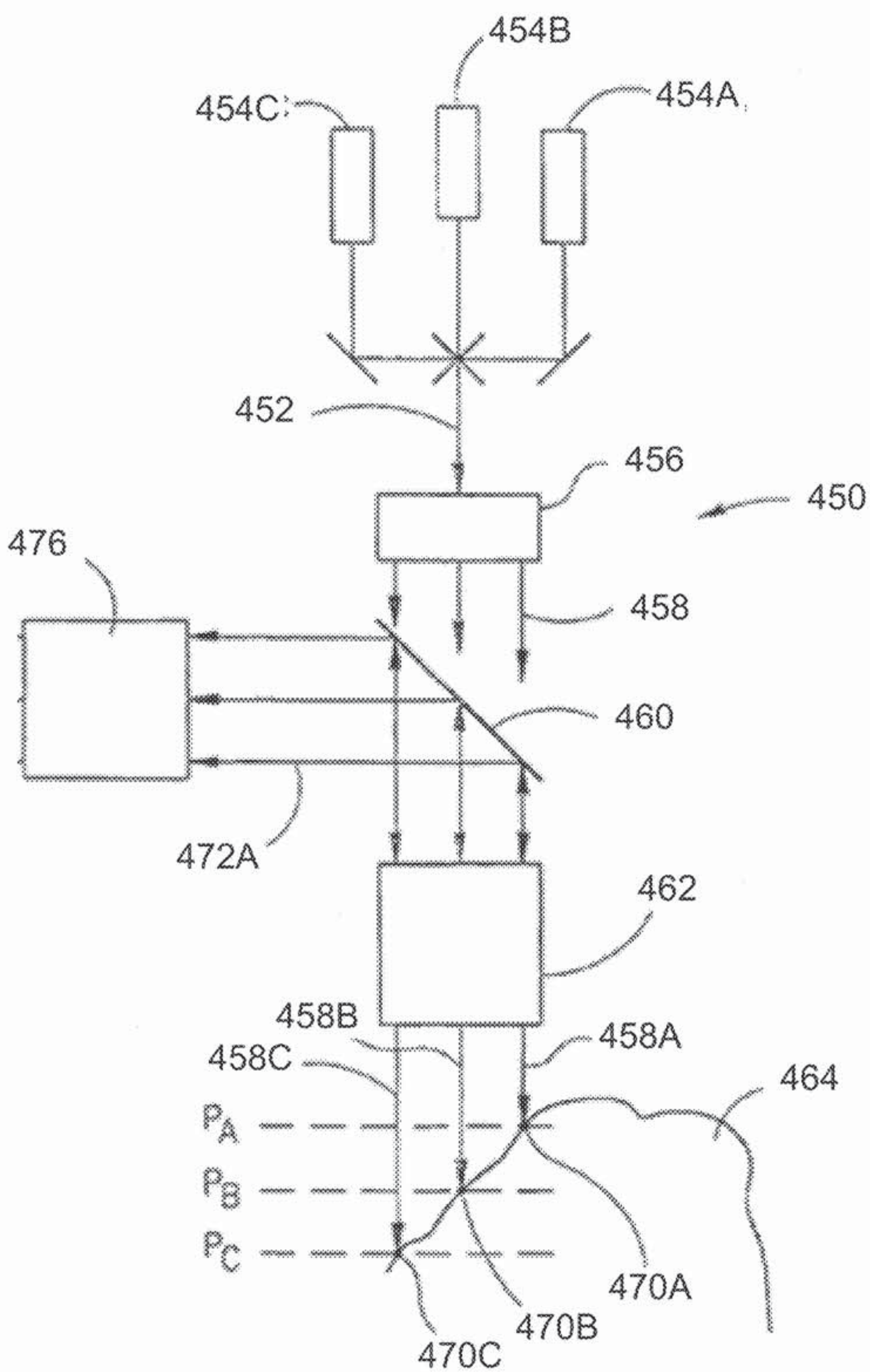

454B
454C
454A
452
456
450
476
458
460
472A
462
458B
458C
458A
464
P_A
P_B
P_C
470A
470B
470C

FIG. 4

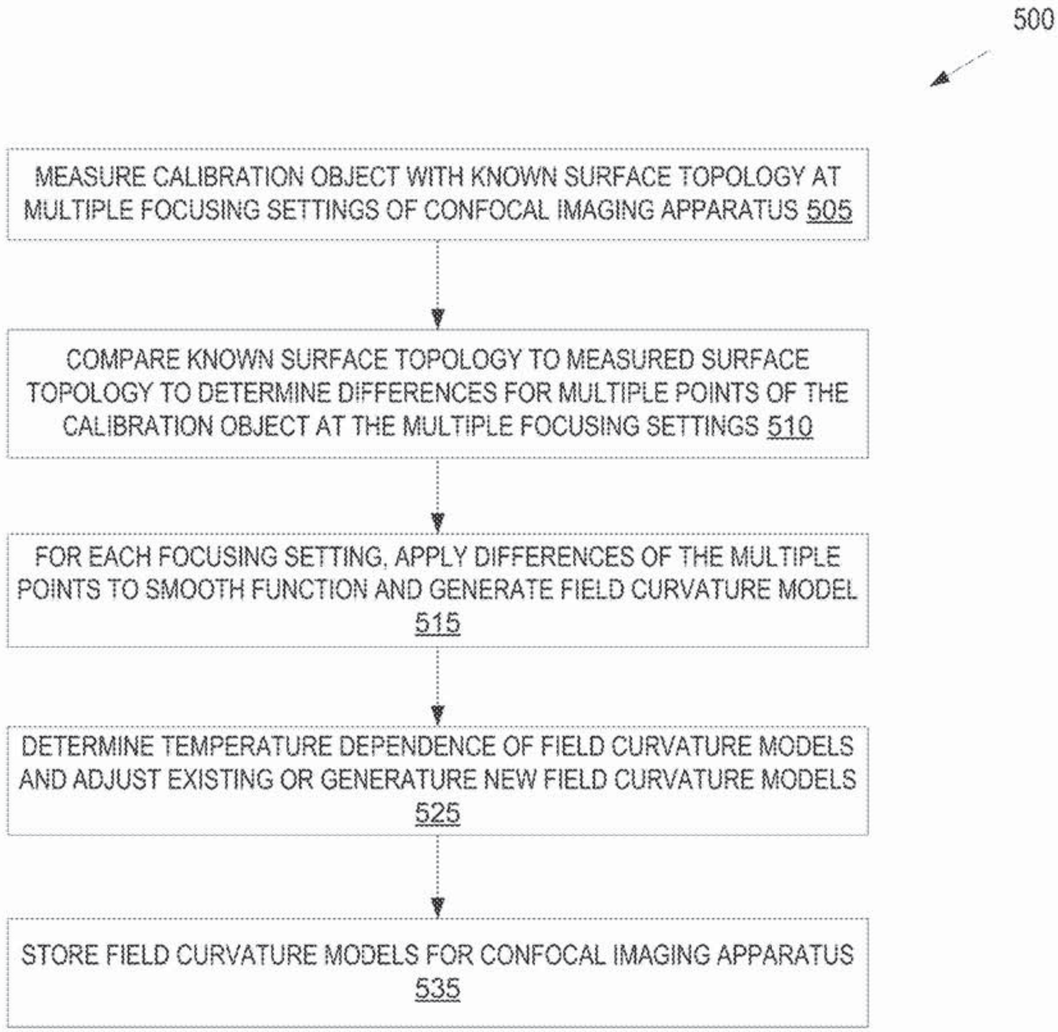

500
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 505
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 510
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SMOOTH FUNCTION AND GENERATE FIELD CURVATURE MODEL 515
DETERMINE TEMPERATURE DEPENDENCE OF FIELD CURVATURE MODELS AND ADJUST EXISTING OR GENERATURE NEW FIELD CURVATURE MODELS 525
STORE FIELD CURVATURE MODELS FOR CONFOCAL IMAGING APPARATUS 535

FIG. 5A

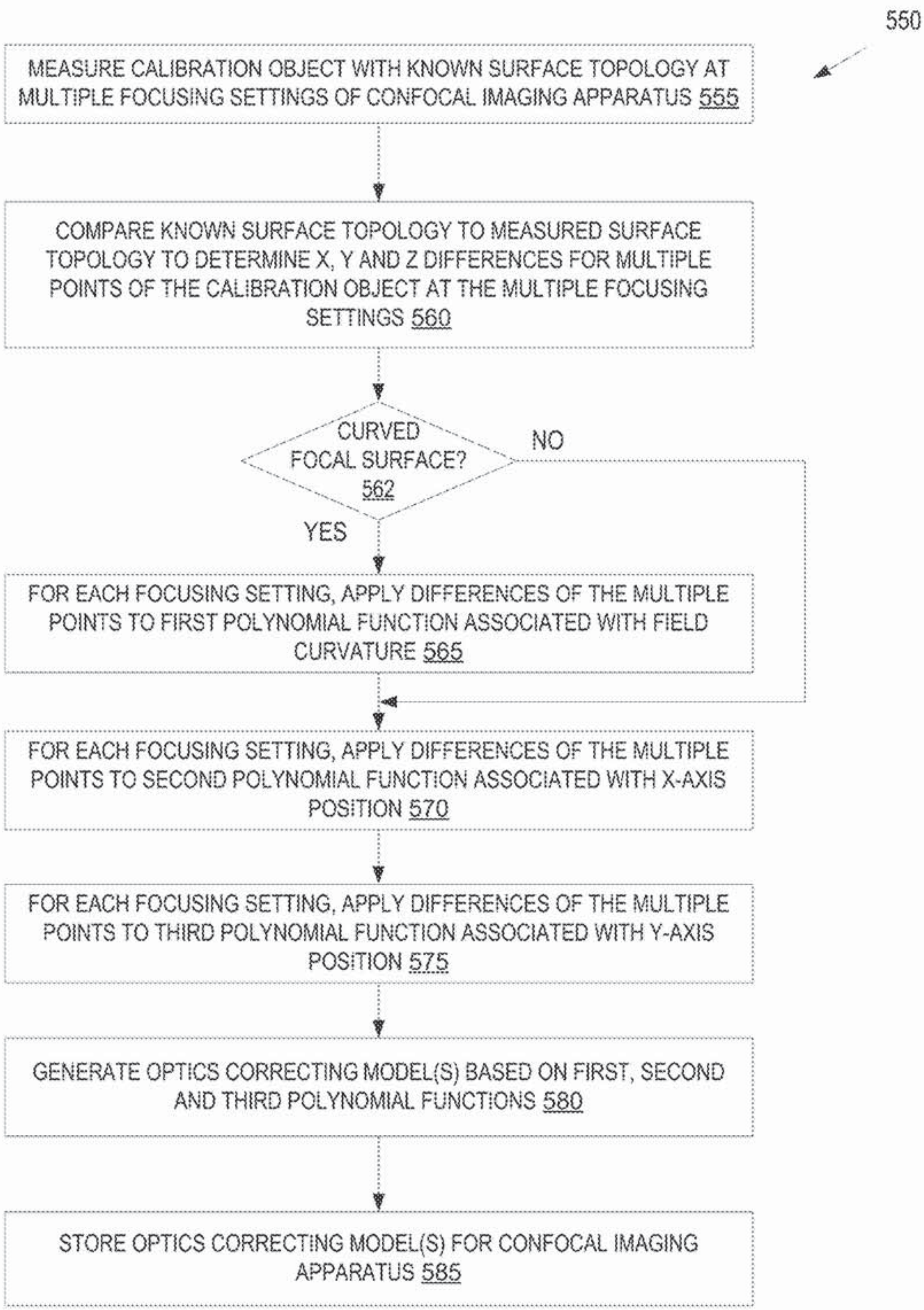

550
MEASURE CALIBRATION OBJECT WITH KNOWN SURFACE TOPOLOGY AT MULTIPLE FOCUSING SETTINGS OF CONFOCAL IMAGING APPARATUS 555
COMPARE KNOWN SURFACE TOPOLOGY TO MEASURED SURFACE TOPOLOGY TO DETERMINE X, Y AND Z DIFFERENCES FOR MULTIPLE POINTS OF THE CALIBRATION OBJECT AT THE MULTIPLE FOCUSING SETTINGS 560
CURVED FOCAL SURFACE? 562
NO
YES
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO FIRST POLYNOMIAL FUNCTION ASSOCIATED WITH FIELD CURVATURE 565
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO SECOND POLYNOMIAL FUNCTION ASSOCIATED WITH X-AXIS POSITION 570
FOR EACH FOCUSING SETTING, APPLY DIFFERENCES OF THE MULTIPLE POINTS TO THIRD POLYNOMIAL FUNCTION ASSOCIATED WITH Y-AXIS POSITION 575
GENERATE OPTICS CORRECTING MODEL(S) BASED ON FIRST, SECOND AND THIRD POLYNOMIAL FUNCTIONS 580
STORE OPTICS CORRECTING MODEL(S) FOR CONFOCAL IMAGING APPARATUS 585

FIG. 5B

590

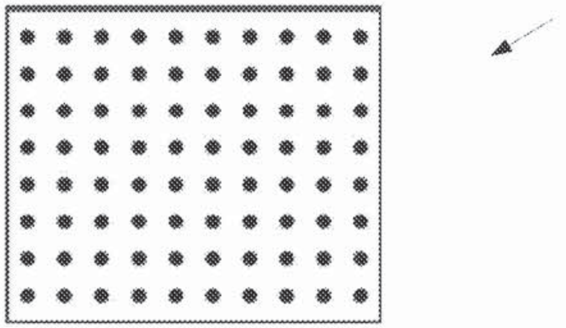


FIG. 5C

594

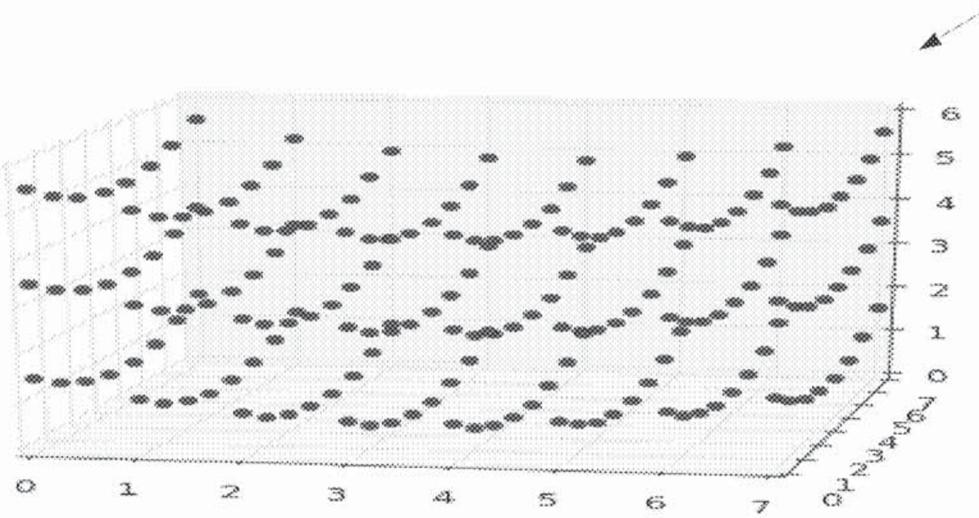


FIG. 5D

597

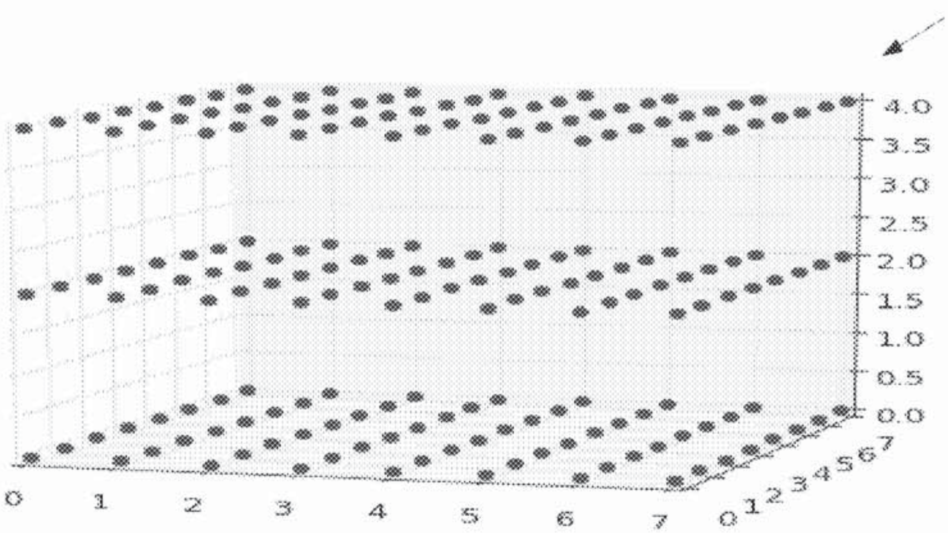


FIG. 5E

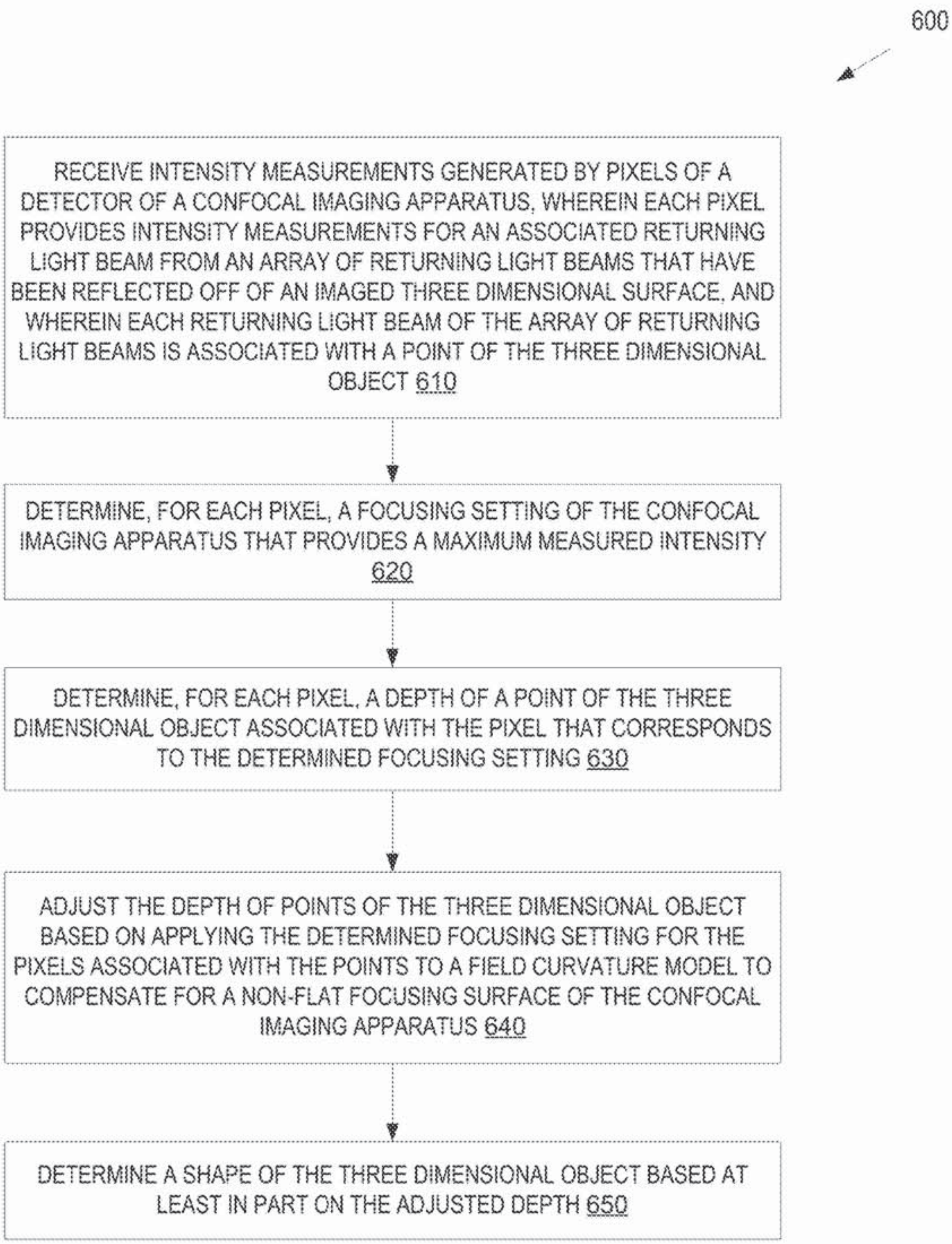

600
RECEIVE INTENSITY MEASUREMENTS GENERATED BY PIXELS OF A DETECTOR OF A CONFOCAL IMAGING APPARATUS, WHEREIN EACH PIXEL PROVIDES INTENSITY MEASUREMENTS FOR AN ASSOCIATED RETURNING LIGHT BEAM FROM AN ARRAY OF RETURNING LIGHT BEAMS THAT HAVE BEEN REFLECTED OFF OF AN IMAGED THREE DIMENSIONAL SURFACE, AND WHEREIN EACH RETURNING LIGHT BEAM OF THE ARRAY OF RETURNING LIGHT BEAMS IS ASSOCIATED WITH A POINT OF THE THREE DIMENSIONAL OBJECT 610
DETERMINE, FOR EACH PIXEL, A FOCUSING SETTING OF THE CONFOCAL IMAGING APPARATUS THAT PROVIDES A MAXIMUM MEASURED INTENSITY 620
DETERMINE, FOR EACH PIXEL, A DEPTH OF A POINT OF THE THREE DIMENSIONAL OBJECT ASSOCIATED WITH THE PIXEL THAT CORRESPONDS TO THE DETERMINED FOCUSING SETTING 630
ADJUST THE DEPTH OF POINTS OF THE THREE DIMENSIONAL OBJECT BASED ON APPLYING THE DETERMINED FOCUSING SETTING FOR THE PIXELS ASSOCIATED WITH THE POINTS TO A FIELD CURVATURE MODEL TO COMPENSATE FOR A NON-FLAT FOCUSING SURFACE OF THE CONFOCAL IMAGING APPARATUS 640
DETERMINE A SHAPE OF THE THREE DIMENSIONAL OBJECT BASED AT LEAST IN PART ON THE ADJUSTED DEPTH 650

FIG. 6

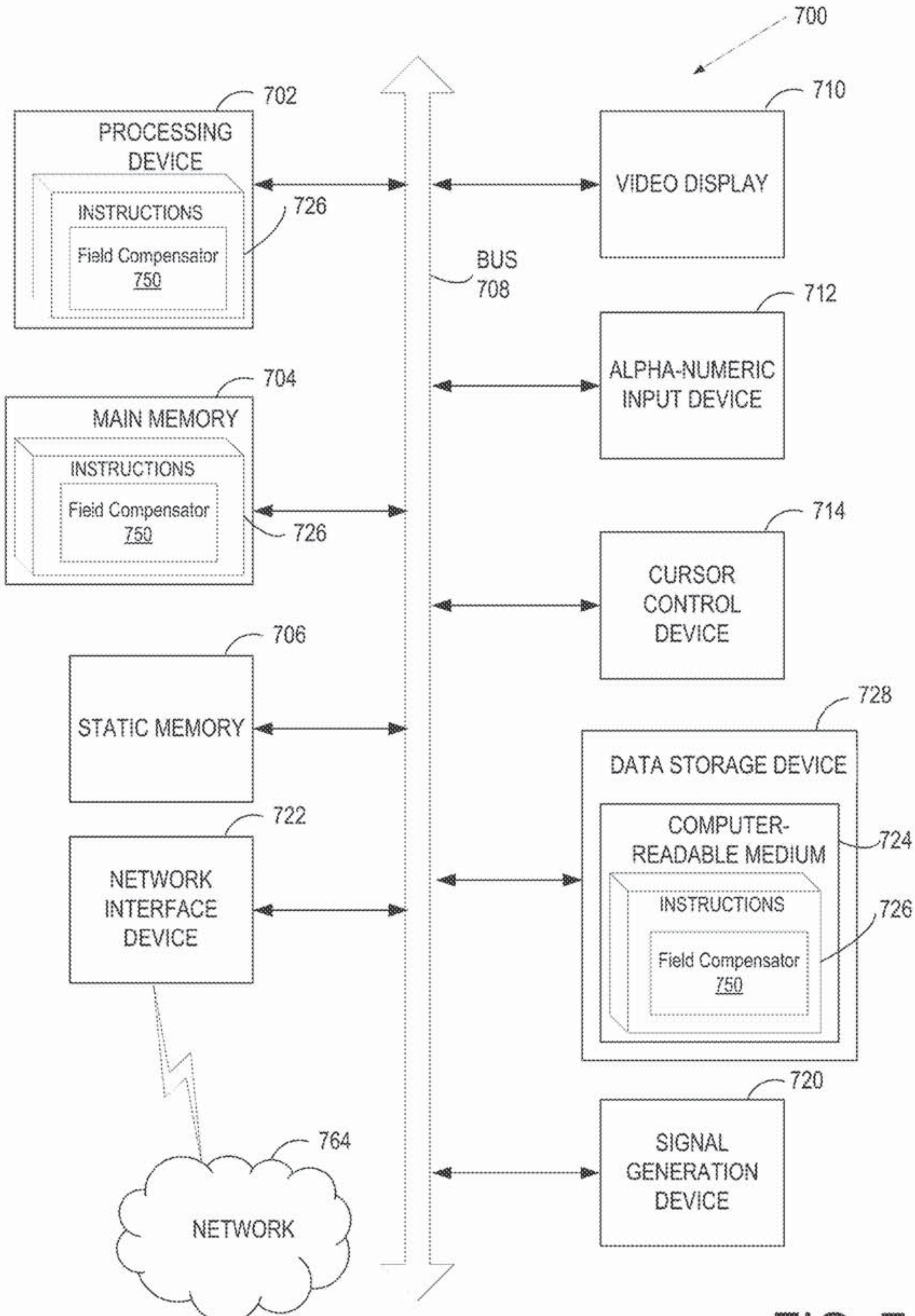

700
702
PROCESSING DEVICE
INSTRUCTIONS
Field Compensator
750
726
BUS
708
710
VIDEO DISPLAY
712
ALPHA-NUMERIC INPUT DEVICE
704
MAIN MEMORY
INSTRUCTIONS
Field Compensator
750
726
714
CURSOR CONTROL DEVICE
706
STATIC MEMORY
728
DATA STORAGE DEVICE
COMPUTER-READABLE MEDIUM
724
INSTRUCTIONS
726
Field Compensator
750
722
NETWORK INTERFACE DEVICE
720
SIGNAL GENERATION DEVICE
764
NETWORK

FIG. 7

IMAGING APPARATUS WITH SIMPLIFIED OPTICAL DESIGN

RELATED APPLICATIONS

This patent application is a continuation application of U.S. patent application Ser. No. 16/286,437, filed Feb. 26, 2019, which is a continuation application of U.S. patent application Ser. No. 15/610,515, filed May 31, 2017, which is a divisional application of U.S. patent application Ser. No. 14/825,173, filed Aug. 13, 2015, which claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application No. 62/037,778, filed Aug. 15, 2014, all of which are herein incorporated by reference.

TECHNICAL FIELD

Embodiments of the present invention relate to the field of imaging and, in particular, to a system and method for performing confocal imaging of a three dimensional surface.

BACKGROUND

A great variety of methods and systems have been developed for direct optical measurement of teeth and the subsequent automatic manufacture of dentures. The term "direct optical measurement" signifies surveying of teeth in the oral cavity of a patient. This facilitates the obtainment of digital constructional data necessary for the computer-assisted design (CAD) or computer-assisted manufacture (CAM) of tooth replacements without having to make any cast impressions of the teeth. Such systems typically include an optical probe coupled to an optical pick-up or receiver such as charge coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) sensor and a processor implementing a suitable image processing technique to design and fabricate virtually the desired product.

One type of system that performs intra-oral scans is a system that uses confocal imaging to image a three dimensional surface. Such systems that use confocal imaging typically include field lenses to flatten an imaging field and enable flat focal planes for emitted light beams. Such flat focal planes ensure that the surface topology of scanned three dimensional surfaces is accurate. However, the field lenses are diverging lenses that open the rays of the light beams. This causes the optics of the confocal imaging apparatus to be enlarged. Additionally, the field lenses should be aligned to ensure accuracy. Such alignment can be a time consuming and challenging process.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

FIG. **1**A illustrates a functional block diagram of a confocal imaging apparatus according to one embodiment.

FIG. **1**B illustrates a block diagram of a computing device that connects to a confocal imaging apparatus, in accordance with one embodiment.

FIG. **2**A illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment.

FIG. **2**B illustrates optics of a confocal imaging apparatus that lacks a field lens, in accordance with another embodiment.

FIG. **2**C illustrates optics of a confocal imaging apparatus with a field lens for which changes in a focusing setting cause changes in magnification, in accordance with another embodiment.

FIG. **3**A is a top view of a probing member of a confocal imaging apparatus that includes a prism, in accordance with an embodiment of the invention.

FIG. **3**B is a longitudinal cross-section through line II-II of the probing member in FIG. **3**A.

FIG. **3**C is a view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. **3**D is a side view of a probing member that includes an internal target, in accordance with one embodiment.

FIG. **4** is a schematic illustration of optics of a confocal imaging apparatus, in accordance with one embodiment.

FIG. **5**A is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface.

FIG. **5**B is a flow chart showing one embodiment of a method for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification.

FIG. **5**C illustrates one example calibration object, in accordance with one embodiment.

FIG. **5**D illustrates a chart showing a distribution of points of a calibration object as measured by a confocal imaging apparatus, in accordance with one embodiment.

FIG. **5**E illustrates a chart showing a distribution of points in a world coordinate system, in accordance with one embodiment.

FIG. **6** is a flow chart showing one embodiment of a method for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model calibrated to a confocal imaging apparatus.

FIG. **7** illustrates a block diagram of an example computing device, in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

Described herein is a confocal imaging apparatus having a non-flat focal surface. The non-flat focal surface may be caused by the optics of the confocal imaging apparatus lacking a field lens. As is discussed in greater detail below, the lack of a field lens in the confocal imaging apparatus introduces challenges but also provides numerous advantages. For example, a confocal imaging apparatus without a field lens is smaller, lighter and easier to manufacture than a confocal imaging apparatus having a field lens. Embodiments discussed herein show how to overcome the challenges in designing and using a confocal imaging apparatus lacking a field lens.

Also described herein is a large field confocal imaging apparatus having focusing optics that change a magnification of a focal surface with changes in a focusing setting. As is discussed in greater detail below, the change in magnification introduces challenges that are overcome in embodiments.

In one embodiment, a confocal imaging apparatus includes an illumination module to generate an array of light beams. Focusing optics of the confocal imaging apparatus perform confocal focusing of an array of light beams onto a non-flat focal surface and direct the array of light beams toward a three dimensional object to be imaged. A translation mechanism of the confocal imaging apparatus adjusts a location of at least one lens to displace the non-flat focal surface along an imaging axis. A detector of the confocal

imaging apparatus measures intensities of an array of returning light beams that are reflected off of the three dimensional object and directed back through the focusing optics. Intensities of the array of returning light beams are measured for locations of the at least one lens for determination of positions on the imaging axis of points of the three dimensional object. Detected positions of one or more points are adjusted to compensate for the non-flat focal surface. Thus, an object may be accurately imaged despite the non-flat focal surface of the confocal imaging apparatus.

FIG. **1**A illustrates a functional block diagram of a confocal imaging apparatus **20** according to one embodiment FIG. **1**B illustrates a block diagram of a computing device **24** that connects to the confocal imaging apparatus **20**. Together, the confocal imaging apparatus **20** and computing device **24** may form a system for generating three dimensional images of scanned objects. The computing device **24** may be connected to the confocal imaging apparatus **20** directly or indirectly and via a wired or wireless connection. For example, the confocal imaging apparatus **20** may include a network interface controller (NIC) capable of communicating via Wi-Fi, via third generation (3G) or fourth generation (4G) telecommunications protocols (e.g., global system for mobile communications (GSM), long term evolution (LTE), Wi-Max, code division multiple access (CDMA), etc.), via Bluetooth, via Zigbee, or via other wireless protocols. Alternatively, or additionally, confocal imaging apparatus may include an Ethernet network interface controller (NIC), a universal serial bus (USB) port, or other wired port. The NIC or port may conned the confocal imaging apparatus to the computing device via a local area network (LAN). Alternatively, the confocal imaging apparatus **20** may connect to a wide area network (WAN) such as the Internet, and may connect to the computing device **24** via the WAN. In an alternative embodiment, confocal imaging apparatus **20** is connected directly to the computing device (e.g., via a direct wired or wireless connection). In one embodiment, the computing device **24** is a component of the confocal imaging apparatus **20**.

Referring now to FIG. **1**A, in one embodiment confocal imaging apparatus **20** includes a semiconductor laser unit **28** that emits a focused light beam, as represented by arrow **30**. The light beam **30** passes through a polarizer **32**. Polarizer **32** polarizes the light beam passing through polarizer **32**. Alternatively, polarizer **32** may be omitted in some embodiments. The light beam then enters into an optic expander **34** that improves a numerical aperture of the light beam **30**. The light beam **30** then passes through an illumination module **38**, which splits the light beam **30** into an array of incident light beams **36**, represented here, for ease of illustration, by a single line. The illumination module **38** may be, for example, a grating or a micro lens array that splits the light beam **30** into an array of light beams **36**. In one embodiment, the array of light beams **36** is an array of telecentric light beams. Alternatively, the array of light beams may not be telecentric.

The confocal imaging apparatus **20** further includes a unidirectional mirror or beam splitter (e.g., a polarizing beam splitter) **40** that passes the array of light beams **36**. A unidirectional mirror **40** allows transfer of light from the semiconductor laser **28** through to downstream optics, but reflects light travelling in the opposite direction. A polarizing beam splitter allows transfer of light beams having a particular polarization and reflects light beams having a different (e.g., opposite) polarization. In one embodiment, the unidirectional mirror or beam splitter **40** has a small central aperture. The small central aperture may improve a measurement accuracy of the confocal imaging apparatus **20**. In one embodiment, as a result of a structure of the unidirectional mirror or beam splitter **40**, the array of light beams will yield a light annulus on an illuminated area of an imaged object as long as the area is not in focus. Moreover, the annulus will become a completely illuminated spot once in focus. This ensures that a difference between measured intensities of out-of focus points and in-focus points will be larger.

Along an optical path of the array of light beams after the unidirectional mirror or beam splitter **40** are confocal focusing optics **42**, and an endoscopic probing member **46**. Additionally, a quarter wave plate may be disposed along the optical path after the unidirectional mirror or beam splitter **40** to introduce a certain polarization to the array of light beams. In some embodiments this may ensure that reflected light beams will not be passed through the unidirectional mirror or beam splitter **40**. Confocal focusing optics **42** may additionally include relay optics (not shown). Confocal focusing optics **42** may or may not maintain the same magnification of an image over a wide range of distances in the Z direction, wherein the Z direction is a direction of beam propagation (e.g., the Z direction corresponds to an imaging axis that is aligned with an optical path of the array of light beams **36**). The relay optics enable the confocal imaging apparatus **20** to maintain a certain numerical aperture for propagation of the array of light beams **36**. The confocal focusing optics **42** and endoscopic probing member **46** are discussed in greater detail with reference to FIGS. **2**A-**2**C.

The endoscopic probing member **46** may include a rigid, light-transmitting medium, which may be a hollow object defining within it a light transmission path or an object made of a light transmitting material, e.g. a glass body or tube. In one embodiment, the endoscopic probing member **46** include a prism such as a folding prism. At its end, the endoscopic probing member **46** may include a mirror of the kind ensuring a total internal reflection. Thus, the mirror may direct the array of light beams towards a teeth segment **26** or other object. The endoscope probing member **46** thus emits array of light beams **48**, which impinge on to surfaces of the teeth section **26**.

The array of light beams **48** are arranged in an X-Y plane, in the Cartesian frame **50**, propagating along the Z axis. As the surface on which the incident light beams hits is an uneven surface, illuminated spots **52** are displaced from one another along the Z axis, at different (X_i, Y_i) locations. Thus, while a spot at one location may be in focus of the confocal focusing optics **42**, spots at other locations may be out-of-focus. Therefore, the light intensity of returned light beams of the focused spots will be at its peak, while the light intensity at other spots will be off peak. Thus, for each illuminated spot, multiple measurements of light intensity are made at different positions along the Z-axis. For each of such (X_i, Y_i) location, the derivative of the intensity over distance (Z) may be made, with the Z_i yielding maximum derivative, Z_0, being the in-focus distance. As pointed out above, the incident light from the array of light beams **48** forms a light disk on the surface when out of focus and a complete light spot when in focus. Thus, the distance derivative will be larger when approaching in-focus position, increasing accuracy of the measurement.

The light scattered from each of the light spots includes a beam travelling initially in the Z axis along the opposite direction of the optical path traveled by the array of light beams **48**. Each returned light beam in an array of returning light beams **54** corresponds to one of the incident light

beams in array of light beams **36**. Given the asymmetrical properties of unidirectional mirror or beam splitter **40**, the returned light beams are reflected in the direction of detection optics **60**.

The detection optics **60** may include a polarizer **62** that has a plane of preferred polarization oriented normal to the plane polarization of polarizer **32**. Alternatively, polarizer **32** and polarizer **62** may be omitted in some embodiments. The array of returning light beams **54** may pass through imaging optics **64** in one embodiment. The imaging optics **64** may be one or more lenses. Alternatively, the detection optics **60** may not include imaging optics **64**. In one embodiment, the array of returning light beams **54** further passes through a matrix **66**, which may be an array of pinholes. Alternatively, no matrix **66** is used in some embodiments. The array of returning light beams **54** are then directed onto a detector **68**.

The detector **68** is an image sensor having a matrix of sensing elements each representing a pixel of the image. If matrix **66** is used, then each pixel further corresponds to one pinhole of matrix **66**. In one embodiment, the detector is a charge coupled device (CCD) sensor. In one embodiment, the detector is a complementary metal-oxide semiconductor (CMOS) type image sensor. Other types of image sensors may also be used for detector **68**. The detector **68** detects light intensity at each pixel.

In one embodiment, detector **68** provides data to computing device **24**. Thus, each light intensity measured in each of the sensing elements of the detector **68**, is then captured and analyzed, in a manner to be described below, by processor **24**.

Confocal imaging apparatus **20** further includes a control module **70** connected both to semiconductor laser **28** and a motor **72**, voice coil or other translation mechanism. In one embodiment, control module **70** is or includes a field programmable gate array (FPGA) configured to perform control operations. Motor **72** is linked to confocal focusing optics **42** for changing a focusing setting of confocal focusing optics **42**. This may adjust the relative location of an imaginary non-flat focal surface of confocal focusing optics **42** along the Z-axis (e.g., in the imaging axis). Control module **70** may induce motor **72** to axially displace (change a location of) one or more lenses of the confocal focusing optics **42** to change the focal depth of the imaginary non-flat focal surface. In one embodiment, motor **72** or confocal imaging apparatus **20** includes an encoder (not shown) that accurately measures a position of one or more lenses of the confocal focusing optics **42**. The encoder may include a sensor paired to a scale that encodes a linear position. The encoder may output a linear position of the one or more lenses of the confocal focusing optics **42**. The encoder may be an optical encoder, a magnetic encoder, an inductive encoder, a capacitive encoder, an eddy current encoder, and so on. After receipt of feedback that the location of the one or more lenses has changed, control module **70** may induce laser **28** to generate a light pulse. Control unit **70** may additionally synchronize image-capturing module **80** from FIG. **1**B to receive and/or store data representative of the light intensity from each of the sensing elements at the particular location of the one or more lenses (and thus of the focal depth of the imaginary non-flat focal surface). In subsequent sequences, the location of the one or more lenses (and thus the focal depth) will change in the same manner and the data capturing will continue over a wide focal range of confocal focusing optics **42**.

Referring now to FIG. **1**B, image capturing module **80** may capture images responsive to receiving image capture commands from the control unit **70**. The captured images may be associated with a particular focusing setting (e.g., a particular location of one or more lenses in the confocal focusing optics as output by the encoder). Image processing module **82** then processes captured images captured over multiple different focusing settings. Image processing module **82** includes a depth determiner **90** and a field compensator **92** for processing image data.

Depth determiner **90** determines the relative intensity in each pixel over the entire range of focal settings of confocal focusing optics **42** from received image data. Once a certain light spot associated with a particular pixel is in focus, the measured intensity will be maximal for that pixel. Thus, by determining the Z_i corresponding to the maximal light intensity or by determining the maximum displacement derivative of the light intensity, for each pixel, the relative position of each light spot along the Z axis can be determined for each pixel. Thus, data representative of the three-dimensional pattern of a surface in the teeth segment **26** or other three dimensional object can be obtained.

In embodiments, the confocal focusing optics **42** of confocal imaging apparatus **20** lack field lenses. The purpose of the field lens is to flatten a focal field and thus produce a flat focal plane for the array of light beams. For confocal imaging apparatuses with field lenses, each light beam from the array of light beams focuses on the same flat focal plane. However, without such field lenses the array of light beams focus on an imaginary non-flat focal surface (e.g., on a curved focal surface). This causes the Z axis information that depth determiner **90** computes to be distorted for many pixels.

Field compensator **92** compensates for the curved field caused by the lack of a field lens. Field compensator **92** may also compensate for changes in a position of the curved focal surface caused by temperature and/or for magnification changes caused by changes in a focusing setting. Field compensator **92** applies a field curvature model **94** and/or other optics compensation model (not shown) to each Z axis measurement of each pixel to correct for field curvature, temperature and/or magnification changes. In one embodiment, a different field curvature model **94** (or other optics compensation model) is applied for each focusing setting of the confocal imaging apparatus **20**. This is because the amount of field curvature and/or magnification may change with changes in the focusing setting. Alternatively, a single field curvature model **94** (or other optics compensation model) may account for the changes in the field curvature caused by changes in the focusing setting and/or for changes in magnification caused by changes in the focusing setting. For each combination of an X,Y pixel location and a focusing setting (e.g., a z-axis position of one or more lenses of the focusing optics), a particular depth adjustment may be applied based on the field curvature model or models. Additionally, an X location adjustment and/or a Y location adjustment bay be applied based on the field curvature model and/or other optics compensation model. In one embodiment, for each combination of an X,Y pixel location, a focusing setting, and a temperature reading or a z-axis position of a measured element whose position changes with changes in temperature, a particular depth adjustment may be applied based on the field curvature model or models. The adjusted depth (z-axis) values represent the actual z-axis values of the imaged surface.

A three-dimensional representation may be constructed based on the corrected measurement data and displayed via a user interface **84**. The user interface **84** may be a graphical user interface that includes controls for manipulating a display of the three-dimensional representation (e.g., view-

ing from different angles, zooming-in or out, etc.). In addition, data representative of the surface topology of the scanned object may be transmitted to remote devices by a communication module **88** for further processing or use (e.g., to generate a three dimensional virtual model of the scanned object).

By capturing, in this manner, an image from two or more angular locations around the structure, e.g. in the case of a teeth segment from the buccal direction, from the lingual direction and optionally from above the teeth, an accurate three-dimensional representation of the teeth segment may be reconstructed. This may allow a virtual reconstruction of the three-dimensional structure in a computerized environment or a physical reconstruction in a CAD/CAM apparatus. For example, a particular application is imaging of a segment of teeth having at least one missing tooth or a portion of a tooth. In such an instance, the image can then be used for the design and subsequent manufacture of a crown or any other prosthesis to be fitted into this teeth segment.

FIG. **2**A illustrates optics **200** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **200** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**.

The optics **200** include an illumination module **38**, a unidirectional mirror or beam splitter **40**, a series of lenses that may correspond to confocal focusing optics **42**, and folding prism **220** arranged along an optical path traversed by an array of light beams **225**. The optical path is shown to be a linear path. However, in embodiments one or more of the components of optics **200** may change a direction of the optical path. For example, the folding prism **220** may include a mirror (not shown) that may reflect light beams at an angle. An example of such a folding prism is shown in FIG. **3**B. Referring back to FIG. **2**, an imaging axis **240** is shown that is aligned to the optical path traversed by the array of light beams **225**. The imaging axis **240** is a Z-axis that represents depth. As used herein, the imaging axis (or Z axis) may be a curvilinear coordinate axis that corresponds to the optical path. Thus, if the optical path changes direction, the imaging axis changes direction correspondingly.

Illumination module **38** is a source of multiple light beams. In one embodiment, illumination module is a micro lens array that divides an incoming light beam into array of light beams **225**. In one embodiment, the array of light beams output by the illumination module **38** is an array of telecentric light beams. Accordingly, chief rays of the array of light beams may be parallel to each other. Unidirectional mirror or beam splitter **40** is disposed along the optical path of the array of light beams, and passes the array of light beams received from the unidirectional mirror or beam splitter **40**.

In one embodiment, the confocal focusing optics are divided into a series of lens groups including a first lens group **205**, a second lens group **215** and a third lens group **210**. First and/or second lens groups **205**, **215** may act as relay optics. The first and second lens groups **205**, **215** are configured to focus the array of light beams and compensate for optical aberrations. Optical aberrations that may be corrected include shape aberrations, coma, stigmatism, and so forth. In one embodiment, the first and second lens groups **205**, **215** are configured to produce an approximately rectangular field having minimal optical distortion. The first lens group **205** and second lens group **215** may have a fixed position relative to each other and to other components of the optics **200**. The third lens group **210** has a variable location that may be adjusted to change a location of a curved focal surface produced by the optics **200**.

The third lens group **210** is movable along the imaging axis (z axis), but has a fixed position normal to the imaging axis. A focusing setting of the focusing optics can be adjusted by moving the third lens group **210** along the imaging axis. Third lens group **210** may be adjusted to perform scanning of an object. To scan an object, the third lens group **210** may be displaced to numerous different locations (encoder positions) along the imaging axis **240**, and images may be taken at each location. In one embodiment, an axial gain of the focusing optics is approximately 7×. Accordingly, a displacement of the third lens group **210** adjusts a location of a curved focal surface **230** by seven times the amount of displacement. For example, a 1 mm displacement of the third lens group **210** causes a position of the curved focal surface (also referred to as a curved focal plane) by 7 mm. This enables the optics **200** to be compact and minimizes movement during operation.

In one embodiment, second lens group **215** focuses the array of light beams **225** into prism **220**, which may be a folding prism. Prism **220** may be configured to provide an appropriate refractive index (e.g., that corresponds to a refractive index of glass).

The optics **200** lack any field lens. A field lens is used to flatten a focal surface (flatten an imaging field) to achieve a flat focal plane. As shown, there is no field lens between the illumination module **38** and the unidirectional mirror or beam splitter **40**. Nor is there a field lens near prism **220** or a field lens between the unidirectional mirror or beam splitter **40** and a detector (not shown). The lack of a field lens introduces numerous advantages over confocal imaging apparatuses that use field lenses. The field lens is a diverging lens that causes a radius of the lenses used for the focusing optics and/or for relay optics to be larger. This in turn increases the amount of material (e.g., glass) used in the lenses and thus increases a weight of the confocal imaging apparatus. Additionally, the larger lenses cause a thickness of the confocal imaging apparatus to be larger. For example, an example confocal imaging apparatus with a field lens includes a largest lens having a distance from an optical axis to an outer perimeter of the lens of about 15 mm. In contrast, the same confocal imaging apparatus without a field lens may include a largest lens having a distance from the optical axis to an outer perimeter of the lens of less than 15 mm (e.g., less than 13 mm or about 9 mm in embodiments).

In a confocal imaging apparatus having a field lens, the field lens may be positioned between the illumination module **38** and the unidirectional mirror or beam splitter **40**. This causes a spacing between the illumination module **38** and the unidirectional mirror or beam splitter **40** to be about 7 mm. Additionally, a corresponding field lens would be placed between the unidirectional mirror or beam splitter **40** and a detector (not shown) at a distance of about 7 mm. In contrast, by eliminating the field lens, the distance **235** between the illumination module **38** and the unidirectional mirror or beam splitter **40** may be less than 7 mm (e.g., less than 5 mm or about 2 mm in embodiments). This further reduces the size of the confocal imaging apparatus.

As mentioned, if a field lens is used in a confocal imaging apparatus, then in actuality two field lenses are used. These two field lenses should be matching field lenses and should be carefully aligned to one another. This alignment can be a time consuming process. Additionally, failure to exactly align these field lenses introduces inaccuracy into the confocal imaging apparatus. Accordingly, an accuracy of the confocal imaging apparatus can be improved and an ease of

manufacture for the confocal imaging apparatus can be improved by eliminating the field lens.

The lack of a field lens causes the focal surface **230** to be a curved focal surface (or other non-flat focal surface). The shape of the curved focal surface **230** may depend on the focusing setting of the focusing optics (e.g., the location of the third lens group **210**). The curved focal surface may introduce significant error into the confocal imaging apparatus, which accounts for the inclusion of field lenses in prior confocal imaging apparatuses. However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the lack of a field lens.

As shown, the confocal focusing optics is a non-telecentric optical system. Accordingly, magnification of an imaged object may change with changes in depth and/or in changes of focal settings. However, such magnification changes (and any accompanying distortion) may be accommodated and corrected by the field compensator based on application of a field curvature model. Alternatively, the confocal focusing optics may operate in a telecentric mode, and distance-introduced magnification changes may be avoided.

FIG. **2**B illustrates optics **250** of a confocal imaging apparatus that lacks a field lens, in accordance with one embodiment. The optics **250** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200**, optics **250** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. The series of lens groups include a first lens group **255** with a fixed position and a second lens group **265** that is movable along an imaging axis **280** corresponding to a direction of propagation for an array of light beams **270**.

The array of light beams **270** are focused onto a curved focal surface **275**. Though the optics **250** are not telecentric, magnification is preserved (fixed) with changes in focusing settings because the array of light beams are collimated between first lens group **255** and second lens group **265**. For optics **250**, axial gain is 1×. Accordingly, a displacement of 1 mm of the second lens group **265** causes a displacement of the curved focal surface of 1 mm.

An object may be placed along the beam path to be imaged. The array of light beams **285** reflect off of the object and an array of returning light beams return back through the series of lens groups. The array of returning light beams **285** is then reflected by the unidirectional mirror (or beam splitter) **40** onto detector **68**. As shown, the optics **250** lack a field lens between the unidirectional mirror or beam splitter **40** and the illumination module **38** and further lack a field lens between the unidirectional mirror or beam splitter **40** and the detector **68**. Accordingly, the focal surface for the optics **250** is a curved focal surface **275**.

Embodiments have been discussed herein with reference to a confocal imaging apparatus that lacks a field lens and that has a curved focal surface. However, in some embodiments the confocal imaging apparatus includes one or more field lenses and thus has a flat focal surface. For such embodiments, the confocal imaging apparatus operates in a non-telecentric mode, and magnification at a focal plane changes with changes in focusing settings of the confocal imaging apparatus.

FIG. **2**C illustrates one example of optics **285** for a confocal imaging apparatus that includes a field lens, in accordance with one embodiment. The optics **285** may correspond to optics of confocal imaging apparatus **20** of FIG. **1**A, such as confocal focusing optics **42**. Similar to optics **200** and optics **250**, optics **285** include an illumination module **38**, a unidirectional mirror (or beam splitter) **40**, and a series of lens groups. However, optics **285** also include a field lens **288** that causes a flat focal plane **299**. The series of lens groups include a first lens group **290** with a fixed position, a second lens group **292** with a fixed position and a third lens group **294** that is movable along an imaging axis **297** corresponding to a direction of propagation for an array of light beams **298**.

The array of light beams **298** are focused onto flat focal plane **299**. Magnification at the flat foal plane **299** changes with changes in focusing settings. The changes in magnification may introduce significant error into the confocal imaging apparatus. Accordingly, the focusing optics for some large field confocal imaging apparatuses maintain the same magnification with changes in focusing settings (e.g., with changes in a position of one or more lenses along an imaging axis). However, embodiments of the present invention provide a field compensator (see, e.g., field compensator **92** of FIG. **1**B) that minimizes or eliminates the error introduced by the change in magnification.

FIGS. **3**A-**3**B illustrate a probing member **300** in accordance with one embodiment. The probing member **300** is made of a light transmissive material such as glass. In one embodiment, the probing member **300** acts as a prism and corresponds to prism **220** of FIG. **2**. Probing member **300** may include an anterior segment **301** and a posterior segment **302**, tightly bonded (e.g., glued) in an optically transmissive manner at **303**. Probing member **300** may additionally include a slanted face **304** covered by a reflective mirror layer **305**. A window **306** defining a sensing surface **307** may be disposed at a bottom end of the anterior segment **301** in a manner leaving an air gap **308**. The window **306** may be fixed in position by a holding structure which is not shown. An array of light rays or beams **309** are represented schematically. As can be seen, the array of light beams **309** are reflected at the walls of the probing member at an angle in which the walls are totally reflective and finally reflect on mirror layer **305** out through the sensing face **307**. The array of light beams **309** focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure).

Various components of the confocal imaging apparatus may dissipate considerable amounts of heat relative to a size of the confocal imaging apparatus. For example, the confocal imaging apparatus may include a CMOS sensor and an FPGA, both of which may produce heat. Accordingly, internal temperatures of the confocal imaging apparatus may rise over time during use. At any given time, different portions of the confocal imaging apparatus may have different temperatures. A temperature distribution within the confocal imaging apparatus is referred to as a thermal state of the confocal imaging apparatus. The thermal state of the confocal imaging apparatus may affect various optical parameters. For example, the thermal state may cause the positions of one or more optical components to move within the confocal imaging apparatus due to expansion of the various components in accordance with thermal expansion coefficients of these components. Additionally, the refractive coefficient of one or more lens of the confocal imaging apparatus may change with changes in the thermal state. Such changes cause measurements produced by the confocal imaging apparatus to change with changes in the internal thermal state. Some regions of the confocal imaging apparatus are more sensitive to thermal change than others (e.g., due to a high optical gain). For example, some optical elements may have an axial gain of up to about 7.5 in an embodiment. For such optical elements, a 10 μm movement

due to changes in the thermal state could cause up to a 75 μm shift in a measurement. Accordingly, in some embodiments, as shown in FIGS. **3C-3D**, an internal target is used to adjust for measurement changes caused by changes in the thermal state. Alternatively, multiple temperature sensors may be disposed within the confocal imaging apparatus and used to determine changes in the thermal state.

FIGS. **3C-3D** illustrate a probing member **370** that includes an internal target **380**, in accordance with one embodiment. The probing member **370** is substantially similar to probing member **300**. For example, probing member **370** may be made of a light transmissive material such as glass, and may act as a prism. Probing member **370** may include an anterior segment **371** and a posterior segment **372**, tightly bonded (e.g., glued) in an optically transmissive manner. Probing member **370** may additionally include a slanted face covered by a reflective mirror layer. A window **376** defining a sensing surface may be disposed at a bottom end of the anterior segment **371**. The window **376** may be glass or another transparent material, and may be fixed in position by a holding structure which is not shown.

Probing member **370** additionally includes internal target **380** secured to the anterior segment **371** of the probing member **370** within a field of view (FOV) of the probing member **370**. The internal target **380** may be a rigid reflective material that will reflect light beams. The internal target **380** may be secured at a fixed position within the probing member **300**. Since the internal target **380** is a part of the probing member **370**, the location of the internal target **380** should remain constant. In one embodiment, the internal target **380** takes up approximately 500 μm to 1 mm of the FOV.

During measurement, an array of light rays or beams **390-392** is projected out of the anterior segment **371**. As can be seen, the internal target **380** is in the path of light beams **390**. Accordingly, the light beams **390** are reflected off of the internal target **380**, which provides a depth (z-axis) measurement of the internal target **380**. Since the internal target **380** is at a fixed position, the measured depth of the internal target **380** should not change. Accordingly, any measured change in the position of the internal target **380** reflects changes in internal optics associated with the thermal state of the confocal imaging apparatus.

The light beams **392** project through the window **376** and focus on a non-flat focal surface **310**, the position of which can be changed by the focusing optics (not shown in this figure). Alternatively, the internal target **380** may be included in an imaging apparatus with a flat focal surface (e.g., an imaging apparatus with a field lens). Such an imaging apparatus may or may not be a confocal imaging apparatus. These light beams **392** may be used to measure the position of an object in the FOV of the confocal imaging apparatus. The measured change in the position of the internal target **380** can be used to correct for measurement errors caused by the thermal state. Any apparent change in the z-axis position of the internal target **380** may be used to apply an adjustment factor to other z-axis measurements of the imaged object to compensate for changes in the focusing optics caused by temperature. Additionally, a change in the z-axis position of the internal target may be used to apply an adjustment to the X and Y pixel measurements in embodiments. In one embodiment, the z-axis position of the internal target and measured points of an object are input into a thermal state compensation model to compensate for the thermal state. In one embodiment, the thermal state compensation model is a three dimensional polynomial function.

FIG. **4** is a schematic illustration of a confocal imaging apparatus **450**, in accordance with one embodiment. In one embodiment, the confocal imaging apparatus **450** corresponds to confocal imaging apparatus **20** of FIG. **1**A. In one embodiment, components of confocal imaging apparatus **20** correspond to like named components illustrated in optics **200** of FIG. **2**. In confocal imaging apparatus **450** a parent light beam **452** may be a combination of light emitted by multiple lasers **454**A, **454**B and **454**C. Alternatively, the parent light beam **452** may be produced by a single laser (e.g., **454**B). An illumination module **456** (e.g., an optic expander) then expands the single parent beam into an array of incident light beams **458**. Incident light beams pass through a unidirectional (e.g., unidirectional) mirror or beam splitter **460**, then through focusing optics **462** towards an object **464** to be imaged.

Parent beam **452** may include multiple different wavelengths, with a different wavelength being transmitted from each laser **454**A-C. Thus, parent light beam **452** and one or more incident light beams in the array of light beams **458** may be composed of multiple different light components. Alternatively, each light beam in the array of light beams may include a single wavelength from the multiple wavelengths of parent beam **452**. Lasers **454**A-C may be arranged such that each light beam focuses on a different curved focal surface, P_A, P_B and P_C, respectively. In the position shown in FIG. **4**, incident light beam **458**A reflects off of the surface at spot **470**A, which in the specific optical arrangement of optics **462** is in the focal point for light component A (emitted by laser **454**A). Thus, a returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel. In one embodiment, the detector is a two-dimensional array of spectrophotometers, e.g. a 3 CHIP CCD sensor. Similarly, different maximal intensity will be reached for spots **470**B and **470**C for light components B and C, respectively. Thus, by using different light components each one focused simultaneously at a different plane, the time used to complete a measurement can be reduced as different focal plane ranges can simultaneously be measured.

In an alternative embodiment, only a single wavelength of light is emitted (e.g., by a single laser). Thus, parent beam **452** and the array of light beams **458** may include a single wavelength. In such an embodiment, each of the light beams in the array of light beams **458** focuses on the same curved focal surface P_C. Thus in the position shown in FIG. **4**, incident light beam **458**A reflects off of the surface at spot **470**A which in the specific focusing setting of focusing optics **462** is at the focal point for focusing optics **462**. Thus, the returned light beam **472**A is measured by a detector **476** that includes a two dimensional array of sensors, each corresponding to a pixel and is registered as the z-axis position for spot **470**C. Similarly, incident light beams **458**A, **458**B reflect off of the surface at spots **470**A and **470**B, respectively. However, the spots **470**A, **470**B are not on the curved focal surface P_C. Accordingly, light is reflected back in a blurred manner from the object **464** for those spots. By changing the focusing setting for focusing optics **462** so that the focal point aligns with spot **470**B and separately with **470**A, corresponding depths associated with those focusing settings may be detected for spots **470**B and **470**A, respectively.

FIG. **5**A is a flow chart showing one embodiment of a method **500** for calibrating a confocal imaging apparatus having an imaginary non-flat focal surface. Method **500** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic,

microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **500** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment, at least some operations of method **500** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described in embodiments herein has a non-flat (e.g., curved) focal surface. This curved focal surface introduces inaccuracies in depth measurements of points of a scanned object. For example, a first point of the object at a center of the confocal imaging apparatus' imaging field may be in focus and thus cause a highest intensity measurement at a depth Z. However, a second point of the object at an edge of the imaging field that has a same depth as the first point may be in focus and cause a highest intensity measurement at a depth Z_i+X due to the non-flat focal surface, where X represents the difference between the focal point at the center of the imaging field and the focal point at the edge of the imaging field. Thus, the non-flat imaging field will cause measurements of the first and second points to yield different depth values even though they are at the same depth. In one embodiment, calibration method **500** is performed to calibrate the confocal imaging apparatus so that the error introduced by the non-flat focal surface can be eliminated.

At block **505** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the find accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a find desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns.

Various calibration objects may be used, a few examples of which are set forth herein. One example calibration object is a sphere with a very accurate radius on an accurate X-Y-Z stage. Another example calibration object is a flat plate with a grid of horizontal and vertical lines printed on a surface of the plate. A flatness of the plate and the line spacing may be very accurate. Another example calibration object is a flat plate with circles or dots printed on a surface of the plate. The flatness of the plate and the size and spacing of the circles may be very accurate. Many other calibration objects may also be used. FIG. **5**C illustrates one example calibration object **590**, which is a flat plate with a grid of precisely spaced circles or dots.

Referring back to FIG. **5**A, the calibration object is measured at each focusing setting (e.g., encoder position) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object.

In one embodiment, the calibration object is mounted to a calibration jig, which may precisely move the calibration object in one or more dimensions. For example, the calibration object **590** may be mounted to the calibration jig, and the calibration jig may be moved along the z-axis. In one embodiment, the calibration jig moves the calibration object in 1 mm increments, with an accuracy of 1 μm. The calibration jig may move the calibration object in such a way as to cover more than the full field of view of the confocal imaging apparatus (e.g., the calibration object may be larger than the FOV of the confocal imaging apparatus) and to cover more than the range for the depth of scanning of the confocal imaging apparatus.

In the example of the calibration object **590**, the calibration object **590** may be scanned in two ways. A first scan may be performed at each depth position of the calibration object **590** using regular confocal scanning. This will provide a z-position for each dot in the coordinate system of the confocal imaging apparatus (e.g., based on the coordinates of the encoder that positions the lens). A second scan may be performed to generate an image of the dots at focus for each focal setting. The image may be used to determine an X, Y position for the center of each dot in pixel coordinates and with sub-pixel accuracy.

At block **510**, the measurements of the calibration object (measurements of the calibration object's surface topology) are compared to a known surface topology of the calibration object. Each point in the calibration object (e.g., each dot in calibration object **590** having a measured x-pixel, y-pixel and encoder value) may be paired to a corresponding real world point (point in a world coordinate system) from the calibration object, where the world coordinate system corresponds to known X, Y, Z coordinates of the calibration object. For example, the X and Y coordinates for calibration object **590** would correspond to known fixed positions of the dots, and the Z coordinate for calibration object **590** would depend on a setting of a calibration jig. For each point of the calibration object, a difference between a measured depth value and a known depth value may be determined. Additionally, for each point of the calibration object, a difference between a measured X and Y position and a known X and Y position may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **515**, the determined differences of the multiple points may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. The function is referred to herein as a un-distortion function. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature(object)}(x,y,Z_{optics})=a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \tag{1}$$

Where x and y are the X, Y coordinates for points on a plane normal to the imaging axis. Alternatively, a higher order polynomial may be used. The smooth function with the solved constants may then be used as an accurate field curvature model. Every parameter may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. This may result in an 18 parameter field curvature model if the above described bivariate quadratic polynomial is used.

Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape). In such an embodiment, a generated model may have a different number of parameters (e.g., 12 parameters if a function describing a conic shape is used). Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS)

method) may be applied to find the best values for the constants. As mentioned, this process may be performed for each focusing setting. This is because the amount of field curvature may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate field curvature model may be generated for each focusing setting. Alternatively, a single field curvature model may be generated that accounts for the changes to the field curvature model due to changes in the focusing setting.

In embodiments, X and Y positions are solved for at the same time that the depth is solved for. For example, differences in X and Y position at different focus settings may also be applied to solve for the constants in the smooth function. Additionally, other types of geometric correction may be solved for as well using this technique. All such geometric corrections may be solved for together. Other types of phenomena that may be corrected for using this technique include magnification change, optical distortion (e.g., non-constant magnification in x and y), optical aberrations, and so on. All such distortions may be solved for together.

FIG. **5D** illustrates a chart **594** showing a distribution of points of the calibration object **590** as measured by the confocal imaging apparatus (in the coordinate system of the confocal imaging apparatus). Chart **594** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots appear to lie on a curved surface. FIG. **5**E illustrates a chart **597** showing a distribution of points in the real world. Chart **597** shows measurements taken with the calibration object **590** at three different z positions. As shown, the dots lie on a plane. After calibration, the transformation for each dot may be determined to correct for optical distortions. Thus, the true world position of each dot may be accurately measured.

At block **525**, a temperature dependence of the confocal imaging apparatus (e.g., the focusing optics and of a lens housing for the focusing optics) is determined. In one embodiment, the operations of one or more of blocks **505-515** are performed at multiple temperatures over a temperature operating range of the confocal imaging apparatus to determine the temperature dependence. Changes in temperature may cause differences in the measured depth values. Accordingly, a temperature dependency may be determined and applied to the field curvature model to create a thermal state correction model. For example, the field curvature model may be modified from x, y, z=F(i, j, encoder) to x, y, z=F(i, j, encoder, T_{state}), where x, y and z represent real world coordinates, i represents an x-pixel, j represents a y-pixel, encoder represents a focal setting (encoder position), and T_{state} represents a thermal state. For such a model that takes into account the thermal state, an estimate of the thermal state should be obtained for each measurement. A thermal state correction model may also be generated for an imaging apparatus with a flat focal surface using the same process as described herein for an imaging apparatus with a curved focal surface.

In one embodiment, opto-mechanical simulation is performed to determine a relationship between temperature and adjustments in calibration of the focusing optics. This relationship may be used to determine a correction that may be applied to all parameters of the generated field curvature model or models, where the amount of correction is based on a current temperature.

In one embodiment, the main change in the focusing optics due to temperature is a focus shift. Curvature of the non-flat focal surface may be practically unchanged by changes in temperature. In one embodiment, a shift in focus for focusing settings may be determined by scanning one or more elements (e.g., an internal target such as internal target **380** of FIGS. **3**C-**3**D) of the confocal imaging apparatus that is near or along the optical path. In one embodiment, the scanned element is on a side of a field of view (FOV) of the confocal imaging apparatus. This element may be kept at the same distance relative to one or more components of the focusing optics. With each scan, when the 3D surface of an object is captured, the edge of the FOV where the internal target is located captures a position of the internal target. Due to the fact that the internal target is part of the confocal imaging apparatus and has a fixed position, detected changes in the position of the internal target are caused by changes in the thermal state. Accordingly, if a focus shift of the internal target is detected from the scan, then an adjustment factor may be applied to the field curvature model to compensate for the thermal state.

In one embodiment, separate field curvature models are generated for each temperature value or range of the confocal imaging apparatus at a particular focusing setting. Alternatively, a single model may be generated for each focusing setting that accounts for changes in temperature. Alternatively, a temperature dependent adjustment factor may be determined and applied to the field curvature model or models based on a measured temperature.

In one embodiment, a simple model may be used that assumes that optical change caused by the thermal state is primarily due to a linear shift in the focal setting (e.g., a backward motion in the encoder position). For such a model, changes caused by the thermal state may be corrected by adding the difference between a current measured internal target position and a reference value to every focal setting (encoder value) before applying the un-distortion function. The simple model may have the form of:

$$x,y,z=F(i,j,\text{encoder}-(\text{internal target position}-\text{reference target position})) \tag{2}$$

where F is the un-distortion function, such as function (1) above.

In another embodiment, a more complex model is used that assumes internal target effects are caused by the focal shift of encoder, but in a complex way. Such a model may have the form of:

$$x,y,z=F(i,j,f(\text{encoder},\text{internal target position})) \tag{3}$$

In another embodiment, a model that corrects for distortions caused by the thermal state assumes that the thermal state changes all optics by a small amount that can be linearly estimated. Such a model may have the form of:

$$x,\ y,\ z = F_{hot}(i,\ j,\ \text{encoder})\frac{(p-a)}{(b-a)} + F_{cold}(i,\ j,\ \text{encoder})\left(1-\frac{(p-a)}{(b-a)}\right) \tag{4}$$

where F_{hot} is the un-distortion function under a hot condition, F_{cold} is the un-distortion function under a cold condition, a is the internal target position in the hot condition, b is the internal target position in the cold position, and p is the measured internal target position.

At block **535**, the one or more generated field curvature models for the confocal imaging apparatus are stored. The field curvature models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the field curvature models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The Field curvature model

(or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface of the confocal imaging apparatus. If calibration information is stored in memory of the confocal imaging apparatus, then the field curvature models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received field curvature models to correct for the field curvature of the confocal imaging apparatus.

FIG. **58** is a flow chart showing one embodiment of a method **550** for calibrating a confocal imaging apparatus for which changes in a focusing setting cause changes in magnification. Method **550** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **550** are performed by a computing device (e.g., computing device **24** of FIG. **1**B). In one embodiment, at least some operations of method **550** are performed by confocal imaging apparatus **20** of FIG. **1**A.

The confocal imaging apparatus described with reference to method **550** may have a non-flat (e.g., curved) focal surface or a flat focal plane. Moreover, the confocal imaging apparatus described with reference to method **550** has focusing optics that are configured so that changes in a focusing setting cause a change in magnification at the focal surface or focal plane. This change in magnification introduces inaccuracies in X and Y position measurements of points of a scanned object. For example, a point of the object might be measured to have a first X and Y position at a first focusing setting, but might be measured to have a second X and Y position at a second focusing setting. Thus, the magnification changes will cause measurements to yield different X, Y values as the focusing setting changes. In one embodiment, calibration method **550** is performed to calibrate the confocal imaging apparatus so that the inaccuracies introduced by the changes in magnification can be eliminated.

At block **555** of method **500**, a calibration object is measured by the confocal imaging apparatus. The calibration object is a high accuracy object with known X, Y and Z coordinates for every point of the calibration object. The accuracy level of the calibration object may define the find accuracy of the confocal imaging apparatus. In one embodiment, the X, Y and Z coordinates for the calibration object are accurate and known to a level of accuracy that is a degree of magnitude higher than a find desired accuracy of the confocal imaging apparatus. For example, if the confocal imaging apparatus is to have a final accuracy to 5 microns, then the calibration object may be accurate to 0.5 microns. Any of the calibration objects described with reference to FIG. **5**A may be used.

The calibration object is measured at each focusing setting (encoder value) of the confocal imaging apparatus. For some types of calibration objects (e.g., the sphere), the calibration object is moved to multiple different X, Y positions for each focusing setting and/or to multiple different X, Y, Z positions for each focusing setting. For other types of calibration objects (e.g., the plates), the calibration object may be moved to multiple different Z positions for each focusing setting. Measurements may be taken for each position of the calibration object. Based on these measurements, a list of coordinates is collected in both the calibration object space (e.g., real world) and in the sensor/optics space (e.g., virtual space). In the calibration object space, each set of coordinates for a point of the object has an X_{obj}, Y_{obj} and Z_{obj} coordinate. These coordinates are known to be accurate due to the known information about the calibration object. In the sensor/optics space, each set of coordinates for a point of the object includes an X_{pix}, Y_{pix}, Z_{optics} coordinate, where X_{pix} and Y_{pix} are determined based on the pixel detecting the point and Z_{optics} is the lens position of the focusing optics (e.g., the focusing setting).

At block **560**, the measurements of the calibration object (measurements of the calibration object's surface topology) may be compared to a known surface topology of the calibration object. For each point of the calibration object, a difference between a measured depth value, X value and/or Y value and a known depth value, X value and/or Y value may be determined. This may be performed for each focusing setting of the confocal imaging apparatus.

At block **562**, it is determined whether the focusing optics have a curved focal surface. If the focusing optics do have a curved focal surface, the method proceeds to block **565**. Otherwise the method proceeds to block **570**.

At block **565**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the field curvature of the confocal imaging apparatus' non-flat focal surface. In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Z_{Field\ Curvature\ (object)}(x,y,Z_{optics})-a_1x^2+a_2y^2+a_3x+a_4y+a_5xy+a_6 \quad (5)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., a function describing a conic shape), such as a polynomial of higher order. The smooth function with the solved constants may then be used for an accurate field curvature model.

At block **570**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional or higher dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on an x-axis caused by changes in the focusing setting (e.g., changes in the Z_{optics} value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$X_{Object}(x,y,Z_{optics})=b_1x^2+b_2y^2+b_3x+b_4y+b_5xy+b_6 \quad (6)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the X coordinate.

At block **575**, the determined differences of the multiple points for the X, Y and/or Z coordinates may be applied to a smooth function (e.g., to a polynomial function such as a three dimensional polynomial function) that may be used to model the changes in magnification of the confocal imaging apparatus on a y-axis caused by changes in the focusing

setting (e.g., changes in the Z_{optics} value). In one embodiment, the determined differences are applied to solve for the constants in a bivariate quadratic polynomial of the form:

$$Y_{Object}(x,y,Z_{optics})=c_1x^2+c_2y^2+c_3x+c_4y+c_5xy+c_6 \quad (7)$$

Where x and y are the X_{pix}, Y_{pix} coordinates in the sensor space. Alternatively, the determined differences may be applied to solve for the constants in another smooth function (e.g., in another three dimensional polynomial function, such as a function describing a conic shape). The smooth function with the solved constants may then be used as an accurate magnification compensation model for the Y coordinate.

Blocks **565**, **570** and **575** have been described as three separate operations. However, in some embodiments a single operation may be performed to solve for each of the x-coordinate, the y-coordinate and the z-coordinate. For example, an un-distortion function having the following form may be solved to determine the x, y and z coordinates.

$$F_X(x,y,z)=a_0+a_1x+a_2y+a_3z+a_4x^2+a_5y^2+a_6z^2+\ldots+a_ixy+\ldots+a_jx^ny^mz^k$$

$$F_Y(x,y,z)=b_0+b_1X+b_2y+b_3z+b_4x^2+b_5y^2+b_6z^2+\ldots+b_ixy+\ldots+b_jx^ny^mz^k$$

$$F_Z(x,y,z)=c_0+c_1x+c_2y+c_3z+c_4x^2+c_5y^2+c_6z^2+\ldots+c_ixy+\ldots+c_jx^ny^mz^k \quad (8)$$

where F_X, F_Y and F_Z are the functions whose results in world coordinates are to be solved for, x and y are pixel coordinates measured by the confocal imaging apparatus, z is a focal setting (e.g., encoder coordinates corresponding to a focal setting), a_i, b_i and c_i are learned parameters, and n, m and k are the maximal degree of the nominal. The function may be selected to minimize a mean square error between the world coordinates and the found positions after the function transformation. Outlier positions may be detected and removed before fitting. In one embodiment, a number of non-zero parameters is constrained.

At block **580**, one or more optics correcting models are generated based on the first second and third polynomial functions (or other smooth functions), such as those represented in equations 5-8. Every parameter for equations 5-8 may be a polynomial that depends on the focusing setting (z-axis value) of the confocal imaging apparatus. In one embodiment, each parameter is modeled as a quadratic change to the Z_{optics} (focusing setting). For example, parameter a_1 may be a parameter having a form:

$$a_i(Z_{Optics})=A+B^*Z_{Optics}+C^*Z_{Optics}^2 \quad (9)$$

Parameters a_2-a_6, b_1-b_6 and c_1-c_6 may be similarly represented. This may result in a 54 parameter model that corrects for full curvature, magnification and distortion of the field of view (FOV).

Linear minimization methods (e.g., linear least square method) and/or non-linear minimization methods (e.g., Broyden-Fletcher-Goldfarb-Shanno (BFGS) method) may be applied to find the best values for the constants at each of blocks **565**, **570** and **575**. As mentioned, these processes may be performed for each focusing setting. This is because the amount of field curvature and magnification may change with different focusing settings of the confocal imaging apparatus. Accordingly, a separate model may be generated for each focusing setting. Alternatively, a single model may be generated that accounts for the changes to the model due to changes in the focusing setting. Note that temperature dependence may also be determined and included in the model as described with reference to block **525** of method **500**. In one embodiment, a temperature dependence is determined, and a model that corrects for thermal state is created, as discussed above with reference to method **500**.

At block **585**, the one or more generated models for the confocal imaging apparatus are stored. The models may be stored in a memory of the confocal imaging apparatus and/or in a memory of a computing device that processes data from the confocal imaging apparatus. In one embodiment, the models are stored in a nonvolatile memory (e.g., a read only memory (ROM), FLASH, or other nonvolatile memory) of the confocal imaging apparatus. The model (or models) may be applied to measurements of the confocal imaging apparatus to correct the error in the depth measurements that are introduced by the non-flat focal surface as well as to correct for inaccuracies caused by changes in magnification. If calibration information is stored in memory of the confocal imaging apparatus, then the models may be sent along with measurement data to a computing device when measurements are taken. The computing device may then use the received models to correct for the field curvature and/or magnification changes of the confocal imaging apparatus.

FIG. **6** is a flow chart showing one embodiment of a method **600** for adjusting depth measurements of a scanned three dimensional object based on application of a field curvature model or other model (e.g., a thermal state compensation model) calibrated to a confocal imaging apparatus or other imaging apparatus (e.g., a stereoscopic imaging apparatus). Method **600** may be performed by processing logic that may comprise hardware (e.g., circuitry, dedicated logic, programmable logic, microcode, etc.), software (e.g., instructions run on a processing device to perform hardware simulation), or a combination thereof. In one embodiment, at least some operations of method **600** are performed by a computing device (e.g., computing device **24** of FIG. **1**B executing image processing module **82**).

At block **605** of method **600**, processing logic receives intensity measurements generated by pixels of a detector of a confocal imaging apparatus. The detector may have a two-dimensional array of pixels, and each pixel may receive a particular light beam of an array of light beams directed at the detector. The array of light beams may be an array of returning light beams that have been reflected off of a surface of the imaged three dimensional object. Thus, each pixel of the detector is associated with a particular point of the three dimensional object and provides intensity measurements for an associated returning light beam from the array of returning light beams.

Each received intensity measurement is associated with a particular focusing setting of the confocal imaging apparatus. Intensity measurements may be received over a range of focusing settings. At block **620**, processing logic determines, for each pixel, a focusing setting of the confocal imaging apparatus that provides a maximum measured intensity.

A relative distance between a probe of the confocal imaging apparatus and a focal point of the confocal imaging apparatus may be known for each focusing setting (encoder value). A point of the imaged object is known to be in focus (e.g., at the focal point) when a measured intensity for that point is maximal. Accordingly, at block **630** processing logic determines, for each pixel, a depth of a point of the three dimensional object associated with that pixel that corresponds to the focusing setting that yielded the maximal intensity. If the imaging apparatus includes an internal target in the FOV of the imaging apparatus, then some pixels will be associated with points on the internal target. Accordingly, a depth of the points of the internal target may also be determined.

As discussed previously herein, the non-flat focal surface and/or magnification changes of the confocal imaging apparatus introduce an error in the depth measurements and/or in the X, Y coordinate measurements. Accordingly, at block **640** processing logic adjusts the determined depths of points of the imaged three dimensional object based on applying the determined focusing settings for the pixels associated with those points to a field curvature model. Processing logic may additionally or alternatively determine X, Y coordinates of the points based on applying the determined focusing settings to the field curvature model or other model. One or more field curvature models and/or other models may be used. For example, a particular field curvature model and/or other model may be associated with each focusing setting. An appropriate field curvature model may be identified based on the focusing setting at which a point on the object came into focus. A particular depth adjustment for that point may then be determined by providing the X, Y coordinates of the pixel into the determined field curvature model. Alternatively, a single field curvature model may be used, and the X, Y coordinates and focusing setting may be input into the field curvature model to determine the depth displacement. In one embodiment, a temperature of the focusing optics is also measured and/or a thermal state is otherwise determined (e.g., using an internal target position), and an additional depth adjustment factor (and/or other optical adjustment) is determined based on the temperature (e.g., using a thermal state compensation model). This additional depth adjustment factor (and/or additional optical adjustment) may then be applied to the measured depths (and/or X and Y coordinates) of all points. In one embodiment, a single model is used that compensates for both the thermal state and field curvature.

At block **650**, processing logic may determine a shape (e.g., surface topology) of the three dimensional object based on the adjusted depths and/or x and y coordinates. Processing logic may then create an accurate virtual three dimensional model of the imaged object.

FIG. **7** illustrates a diagrammatic representation of a machine in the example form of a computing device **700** within which a set of instructions, for causing the machine to perform any one or more of the methodologies discussed herein, may be executed. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet computer, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein. In one embodiment, computing device **700** corresponds to computing device **24** of FIG. **1**B.

The example computing device **700** includes a processing device **702**, a main memory **704** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM), etc.), a static memory **706** (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory (e.g., a data storage device **728**), which communicate with each other via a bus **708**.

Processing device **702** represents one or more general-purpose processors such as a microprocessor, central processing unit, or the like. More particularly, the processing device **702** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processing device **702** may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. Processing device **702** is configured to execute the processing logic (instructions **726**) for performing operations and steps discussed herein.

The computing device **700** may further include a network interface device **722** for communicating with a network **764** or other device. The computing device **700** also may include a video display unit **710** (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)), an alphanumeric input device **712** (e.g., a keyboard), a cursor control device **714** (e.g., a mouse), and a signal generation device **720** (e.g., a speaker).

The data storage device **728** may include a machine-readable storage medium (or more specifically a non-transitory computer-readable storage medium) **724** on which is stored one or more sets of instructions **726** embodying any one or more of the methodologies or functions described herein. A non-transitory storage medium refers to a storage medium other than a carrier wave. The instructions **726** may also reside, completely or at least partially, within the main memory **704** and/or within the processing device **702** during execution thereof by the computer device **700**, the main memory **704** and the processing device **702** also constituting computer-readable storage media.

The computer-readable storage medium **724** may also be used to store a field compensator **750** which may correspond to field compensator **92** of FIG. **1**B. The computer readable storage medium **724** may also store a software library containing methods that call the field compensator **750**. While the computer-readable storage medium **724** is shown in an example embodiment to be a single medium, the term "computer-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "computer-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present invention. The term "computer-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent upon reading and understanding the above description. Although embodiments of the present invention have been described with reference to specific example embodiments, it will be recognized that the invention is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense. The scope of the

invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A method of generating a three-dimensional virtual model of an intraoral object, comprising:

capturing, by an imaging apparatus for performing intraoral scans, surface scan data of the intraoral object while changing a position of at least one lens of focusing optics of the imaging apparatus, wherein the surface scan data comprises depth data for a plurality of points of the intraoral object;

adjusting the depth data for one or more of the plurality of points based at least in part on the position of the at least one lens associated with the depth data for the one or more of the plurality of points using one or more compensation models, wherein the one or more compensation models compensate for changes in magnification associated with different positions of the at least one lens, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different positions of the at least one lens; and

generating the three-dimensional virtual model of the intraoral object using the adjusted depth data.

2. The method of claim 1, wherein the focusing optics comprise a non-flat focal surface that distorts the depth data for the one or more of the plurality of points, and wherein the depth data is adjusted to compensate for the non-flat focal surface.

3. The method of claim 2, wherein the non-flat focal surface comprises a curved focal plane and the depth data is adjusted to compensate for a curvature of the curved focal plane.

4. The method of claim 1, wherein the imaging apparatus comprises a non-telecentric optical system, wherein adjustments to the position of the at least one lens cause a change in magnification of a focal surface of the focusing optics, the method further comprising:

adjusting at least one of a position along an x-axis or a position along a y-axis for the one or more of the plurality of points to compensate for the change in magnification of the focal surface for the one or more of the plurality of points.

5. The method of claim 1, wherein a focal surface of the focusing optics changes with changes in temperature, and wherein the depth data is adjusted to compensate for the change in the focal surface caused by the current temperature of the focusing optics for the one or more of the plurality of points.

6. The method of claim 1, wherein an optical system of the imaging apparatus lacks a field lens, wherein the lack of the field lens causes distortion of the depth data for the one or more of the plurality of points, and wherein the depth data is adjusted to compensate for the distortion of the depth data caused by the lack of the field lens.

7. The method of claim 1, wherein:

the imaging apparatus comprises a detector having a plurality of pixels;

each pixel of the plurality of pixels captures the surface scan data for a corresponding point of the plurality of points of the intraoral object; and

capturing the surface scan data comprising the depth data comprises:

determining, for each pixel of the plurality of pixels, a focusing setting of the focusing optics for which a point associated with the pixel is in focus; and

determining, for each pixel of the plurality of pixels, a depth of the point associated with the pixel that corresponds to the determined focusing setting.

8. The method of claim 7, wherein adjusting the depth data for the one or more of the plurality of points comprises applying the determined focusing setting for the pixels associated with the one or more of the plurality of points to at least one of a field curvature model, a thermal state compensation model or a magnification compensation model.

9. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, wherein at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens;

a detector to generate surface scan data by measuring returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the returning light is to be measured for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object, the surface scan data comprising the depth data; and

one or more processor to:

adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models, wherein the one or more compensation models compensate for changes in magnification associated with different locations of the at least one lens, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens; and

generate a three-dimensional virtual model using the adjusted depth data.

10. The imaging apparatus of claim 9, wherein the optical system comprises a non-flat focal surface that distorts the depth data for the one or more of the plurality of points, and wherein the one or more processor is to adjust the depth data to compensate for the non-flat focal surface.

11. The imaging apparatus of claim 10, wherein the non-flat focal surface comprises a curved focal plane, and wherein the one or more processor is to adjust the depth data to compensate for a curvature of the curved focal plane.

12. The imaging apparatus of claim 10, wherein a shape of the non-flat focal surface changes with changes in the location of the at least one lens.

13. The imaging apparatus of claim 9, wherein the one or more processor is further to:

determine a current temperature of the optical system, wherein the focal surface of the focusing optics changes with changes in temperature; and

adjust the depth data to compensate for the change in the focal surface caused by the current temperature of the optical system for the one or more of the plurality of points.

14. The imaging apparatus of claim **9**, wherein the optical system lacks a field lens, wherein the lack of the field lens causes distortion of the depth data for the one or more of the plurality of points, and wherein the one or more processor is further to:

adjust the depth data to compensate for the distortion of the depth data caused by the lack of the field lens.

15. The imaging apparatus of claim **9**, wherein:

the detector comprises a plurality of pixels, wherein each pixel of the plurality of pixels is to capture the surface scan data for a corresponding point of the plurality of points of the intraoral object; and

the one or more processor is further to:

determine, for each pixel of the plurality of pixels, a focusing setting of the focusing optics for which a point associated with the pixel is in focus; and

determine, for each pixel of the plurality of pixels, a depth of the point associated with the pixel that corresponds to the determined focusing setting.

16. The imaging apparatus of claim **15**, wherein to adjust the depth data for the one or more of the plurality of points the one or more processor applies the determined focusing setting for the pixels associated with the one or more of the plurality of points to at least one of a field curvature model, a thermal state compensation model or a magnification compensation model.

17. The imaging apparatus of claim **9**, further comprising:

a beam splitter disposed along the optical path between the light source and the focusing optics, wherein the beam splitter directs the light from the light source towards the focusing optics and directs the returning light from the focusing optics to the detector;

wherein the optical system is characterized in having an absence of a field lens.

18. The imaging apparatus of claim **9**, wherein the light source comprises an illumination module configured to generate a pattern of light in an x-y plane.

19. The imaging apparatus of claim **9**,

wherein the plurality of lenses comprise:

a first lens;

a second lens, the second lens having a fixed location relative to the first lens; and

a third lens disposed between the first lens and the second lens, the third lens having a variable location that is adjustable by the translation mechanism, wherein the focusing optics comprises the third lens.

20. The imaging apparatus of claim **9**, wherein the optical system is a non-telecentric optical system, wherein adjustments to the position of the at least one lens cause a change in magnification of the focal surface of the optical system, and wherein the one or more processor is further to:

adjust at least one of a position along an x-axis or a position along a y-axis for the one or more of the plurality of points to compensate for the change in magnification of the focal surface for the one or more of the plurality of points.

21. The imaging apparatus of claim **9**, wherein the imaging apparatus is a confocal imaging apparatus and the focusing optics are confocal focusing optics.

22. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity, the focusing optics comprising at least one lens of the plurality of lenses;

a translation mechanism to adjust a location of the at least one lens to displace the focal surface along an imaging axis defined by the optical path, wherein adjustments to the location of the at least one lens cause a change in magnification of the focal surface;

a detector to measure returning light that is reflected off of the three dimensional object and directed back through the focusing optics; and

one or more processor to:

determine positions of a plurality of points of the three dimensional object based on the measured returning light; and

adjust the determined positions of one or more of the plurality of points to compensate for respective magnifications of the focal surface associated with respective locations of the at least one lens.

23. The imaging apparatus of claim **22**, wherein the focusing optics perform the focusing of the light onto a non-flat focal surface caused by a lack of a field lens in the optical system.

24. The imaging apparatus of claim **23**, wherein the non-flat focal surface comprises a curved focal plane, wherein the determined positions for the one or more of the plurality of points are to be adjusted to compensate for a curvature of the curved focal plane, and wherein a shape of the non-flat focal surface changes with changes in the location of the at least one lens.

25. The imaging apparatus of claim **22**, wherein the determined positions of the plurality of points comprise determined depths of the plurality of points, and wherein the one or more processor is to adjust the determined depths of the one or more of the plurality of points using one or more compensation models, wherein the one or more compensation models compensate for at least one of a curvature of the focal surface or changes in a position of the focal surface caused by changes in temperature within the imaging apparatus, and wherein the one or more compensation models provide different adjustments to the determined depths of the one or more of the plurality of points for different locations of the at least one lens.

26. The imaging apparatus of claim **22**, wherein the one or more processor is to adjust at least one of a position along an x-axis or a position along a y-axis for the one or more of the plurality of points to compensate for the change in magnification of the focal surface for the one or more of the plurality of points.

27. The imaging apparatus of claim **22**, wherein the light source comprises an illumination module configured to generate a pattern of light in an x-y plane.

28. The imaging apparatus of claim **22**, wherein the imaging apparatus is a confocal imaging apparatus and the focusing optics are confocal focusing optics.

29. The imaging apparatus of claim **22**, wherein the one or more processor is further to:

determine a current temperature of the optical system, wherein the focal surface of the optical system changes with changes in temperature; and

adjust the determined positions of the one or more of the plurality of points to compensate for the change in the

focal surface caused by the current temperature of the optical system for the one or more of the plurality of points.

30. A method of generating a three-dimensional virtual model of an intraoral object, comprising:

capturing, by an imaging apparatus for performing intraoral scans, surface scan data of the intraoral object while changing a position of at least one lens of focusing optics of the imaging apparatus, wherein the surface scan data comprises depth data for a plurality of points of the intraoral object;

adjusting the depth data for one or more of the plurality of points based at least in part on the position of the at least one lens associated with the depth data for the one or more of the plurality of points using one or more compensation models, wherein the one or more compensation models compensate for a curvature of a focal surface of the focusing optics, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different positions of the at least one lens; and

generating the three-dimensional virtual model of the intraoral object using the adjusted depth data.

31. A method of generating a three-dimensional virtual model of an intraoral object, comprising:

capturing, by an imaging apparatus for performing intraoral scans, surface scan data of the intraoral object while changing a position of at least one lens of focusing optics of the imaging apparatus, wherein the surface scan data comprises depth data for a plurality of points of the intraoral object;

adjusting the depth data for one or more of the plurality of points based at least in part on the position of the at least one lens associated with the depth data for the one or more of the plurality of points using one or more compensation models, wherein the one or more compensation models compensate for changes in a position of a focal surface caused by changes in temperature within the imaging apparatus, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different positions of the at least one lens; and

generating the three-dimensional virtual model of the intraoral object using the adjusted depth data.

32. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, wherein at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens;

a detector to generate surface scan data by measuring returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the returning light is to be measured for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object, the surface scan data comprising the depth data; and

one or more processor to:

adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models, wherein the one or more compensation models compensate for a curvature of the focal surface, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens; and

generate a three-dimensional virtual model using the adjusted depth data.

33. An imaging apparatus for performing intraoral scans, comprising:

a light source to provide light;

an optical system comprising a plurality of lenses disposed along an optical path of the light, wherein the optical system comprises focusing optics to perform focusing of the light onto a focal surface and to direct the light toward a three dimensional object to be imaged in an oral cavity;

a translation mechanism to adjust a location of at least one lens of the plurality of lenses to displace the focal surface along an imaging axis defined by the optical path, wherein the at least one lens is a lens of the focusing optics, wherein at least one of a shape or a magnification of the focal surface changes with changes in the location of the at least one lens;

a detector to generate surface scan data by measuring returning light that is reflected off of the three dimensional object and directed back through the focusing optics, wherein the returning light is to be measured for a plurality of locations of the at least one lens for determination of depth data for a plurality of points of the three dimensional object, the surface scan data comprising the depth data; and

one or more processor to:

adjust the depth data for one or more of the plurality of points based at least in part on the location of the at least one lens associated with the depth data using one or more compensation models, wherein the one or more compensation models compensate for changes in a position of the focal surface caused by changes in temperature within the imaging apparatus, and wherein the one or more compensation models provide different adjustments to the depth data for the one or more of the plurality of points for the different locations of the at least one lens; and

generate a three-dimensional virtual model using the adjusted depth data.

* * * * *

Exhibit 4

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Food and Drug Administration
10903 New Hampshire Avenue
Document Control Center – WO66-G609
Silver Spring, MD 20993-0002

April 28, 2016

3Shape A/S
Ms. Hanne Nielsen
Regulatory Affairs Manager
Holmens Kanal 7
DK-1060 Copenhagen
DENMARK

Re: K152086
Trade/Device Name: 3Shape Ortho System ™
Regulation Number: 21 CFR 872.5470
Regulation Name: Orthodontic Plastic Bracket
Regulatory Class: II
Product Code: PNN, LLZ
Dated: March 15, 2016
Received: March 18, 2016

Dear Ms. Nielsen:

We have reviewed your Section 510(k) premarket notification of intent to market the device referenced above and have determined the device is substantially equivalent (for the indications for use stated in the enclosure) to legally marketed predicate devices marketed in interstate commerce prior to May 28, 1976, the enactment date of the Medical Device Amendments, or to devices that have been reclassified in accordance with the provisions of the Federal Food, Drug, and Cosmetic Act (Act) that do not require approval of a premarket approval application (PMA). You may, therefore, market the device, subject to the general controls provisions of the Act. The general controls provisions of the Act include requirements for annual registration, listing of devices, good manufacturing practice, labeling, and prohibitions against misbranding and adulteration. Please note: CDRH does not evaluate information related to contract liability warranties. We remind you, however, that device labeling must be truthful and not misleading.

If your device is classified (see above) into either class II (Special Controls) or class III (PMA), it may be subject to additional controls. Existing major regulations affecting your device can be found in the Code of Federal Regulations, Title 21, Parts 800 to 898. In addition, FDA may publish further announcements concerning your device in the Federal Register.

Please be advised that FDA's issuance of a substantial equivalence determination does not mean that FDA has made a determination that your device complies with other requirements of the Act or any Federal statutes and regulations administered by other Federal agencies. You must comply with all the Act's requirements, including, but not limited to: registration and listing (21 CFR Part 807); labeling (21 CFR Part 801); medical device reporting (reporting of medical device-related adverse events) (21 CFR 803); good manufacturing practice requirements as set forth in the quality systems (QS) regulation (21 CFR Part 820); and if applicable, the electronic product radiation control provisions (Sections 531-542 of the Act); 21 CFR 1000-1050.

If you desire specific advice for your device on our labeling regulation (21 CFR Part 801), please contact the Division of Small Manufacturers, International and Consumer Assistance at its toll-free number (800) 638-2041 or (301) 796-7100 or at its Internet address http://www.fda.gov/MedicalDevices/ResourcesforYou/Industry/default.htm. Also, please note the regulation entitled, "Misbranding by reference to premarket notification" (21CFR Part 807.97). For questions regarding the reporting of adverse events under the MDR regulation (21 CFR Part 803), please go to http://www.fda.gov/MedicalDevices/Safety/ReportaProblem/default.htm for the CDRH's Office of Surveillance and Biometrics/Division of Postmarket Surveillance.

You may obtain other general information on your responsibilities under the Act from the Division of Small Manufacturers, International and Consumer Assistance at its toll-free number (800) 638-2041 or (301) 796-7100 or at its Internet address http://www.fda.gov/MedicalDevices/ResourcesforYou/Industry/default.htm.

Sincerely yours,

Tina Kiang -
S

for Erin I. Keith, M.S.
Director
Division of Anesthesiology, General Hospital,
Respiratory, Infection Control and
Dental Devices
Office of Device Evaluation
Center for Devices and
Radiological Health

Enclosure

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Food and Drug Administration

Indications for Use

Form Approved: OMB No. 0910-0120
Expiration Date: January 31, 2017
See PRA Statement below.

510(k) Number *(if known)*
K152086

Device Name
3Shape Ortho System™

Indications for Use *(Describe)*
3Shape Ortho System™ is intended for use as a medical front-end device providing tools for management of orthodontic models, systematic inspection, detailed analysis, treatment simulation and virtual appliance design options (Custom metal bands, Export of Models, Indirect Bonding Transfer Media) based on 3D models of the patient's dentition before the start of an orthodontic treatment. It can also be applied during the treatment to inspect and analyze the progress of the treatment It can be used at the end of the treatment to evaluate if the outcome is consistent with the planned/desired treatment objectives.
The use of the Ortho System™ requires the user to have the necessary training and domain knowledge in the practice of orthodontics, as well as to have received a dedicated training in the use of the software.

Type of Use *(Select one or both, as applicable)*

[X] Prescription Use (Part 21 CFR 801 Subpart D) [ ] Over-The-Counter Use (21 CFR 801 Subpart C)

CONTINUE ON A SEPARATE PAGE IF NEEDED.

510(K) SUMMARY – Traditional 510(K)

Submitter Information

A Company Name:	3Shape A/S
B Company Address:	Holmens Kanal 7 DK-1060 Copenhagen K
C Company Phone: Company Fax:	+45 7027 2620 +45 7027 2621
D Contact Person:	Hanne Nielsen Regulatory Affairs Manager
E Date Summary Prepared:	April 25, 2016

Device Identification

A Trade/proprietary Name:	3Shape Ortho System™
B Common Name:	Orthodontic Plastic Brackets
C Device Classification Name:	Orthodontic Treatment Planning and Diagnosis Software
C Regulation Number:	872.5470
C Classification:	Class II
D Product Code:	PNN (Orthodontic Software); LLZ

Predicate Device

The 3Shape Ortho System™ Software has the same intended uses and technical characteristics as primary predicate OrthoCAD iQ (K082207) from Cadent Inc. and reference predicate Dolphin Imaging from Patterson Dental Supply (K110430) as listed in "Volume 005, Comparison to Predicate Devices, Table 1: Predicates".

Based on the information and supporting documentation provided, the 3Shape Ortho System™ Software and the primary predicate (OrthoCAD) have same intended use. Both software devices are used by Dental Professionals in orthodontic treatment planning (before, during, after treatment) covering management of patients and models, inspection, 2D and 3D measurement and orthodontic analysis of models, 2D & 3D treatment simulation, as well as virtual appliance preparation, handling and export, and they are both providing device output. Additionally, the indirect bonding functionality of both systems is intended for use with commercially available brackets and wires. Therefore, the 3Shape Ortho System™ Software and the primary predicate (OrthoCAD) are found to be similar in their intended use, supported anatomic areas and the majority of the available features and functionalities.

Indications for Use

3Shape Ortho System™ is intended for use as a medical front-end device providing tools for management of orthodontic models, systematic inspection, detailed analysis, treatment simulation and virtual appliance design options (Custom Metal Bands, Export of Models, Indirect Bonding Transfer Media) based on 3D models of the patient's dentition before the start of an orthodontic treatment. It can also be applied during the treatment to inspect and analyze the progress of the treatment. It can be used at the end of the treatment to evaluate if the outcome is consistent with the planned/desired treatment objectives.

The use of the Ortho System™ requires the user to have the necessary training and domain knowledge in the practice of orthodontics, as well as to have received a dedicated training in the use of the software.

Device Description

3Shape's Ortho System™ is a software system used for the management of 3D scanned orthodontic models of the patients, orthodontic diagnosis by measuring, analyzing, inspecting and visualize 3D scanned orthodontic models, virtual planning of orthodontic treatments by simulating tooth movements, virtual placement of orthodontic brackets on the 3D models and design of orthodontic appliances based on 3D scanned orthodontic models, including transfer methods for indirect bonding of brackets. Output includes only Export Model (also called dental casts), Custom Metal Bands (also called metal bands), and Indirect Bonding Transfer Trays (also called orthodontic bracket placement trays). All devices are to be fabricated from FDA cleared materials.

The device has no patient contact.

Scientific Concept

The underlying scientific concept of the Ortho System™ is to apply digital imaging tools for in orthodontic case archiving, diagnosis, treatment planning and CAD design of customized appliances.

Virtual positioning of brackets is possible with the use of encrypted libraries of the bracket geometry provided by the manufacturers and available through a dedicated download center in the software.

The system supports the following types of digital data: DICOM, STL, JPG, BMP, PNG.

Summary of the technological characteristics

Ortho System™ is a software only device programmed in Delphi and has the following PC/laptop hardware requirements:

Item	Minimum Requirements
OS:	Windows 7 or 8 64-bit
RAM:	8 GB
Monitor Resolution:	1280x800 or similar
Video Card Memory:	1 GB GeForce

Available HDD Space:	250 GB
CPU:	IntelCore i5 or equivalent
Network:	Network Internet connection
Mouse:	With the wheel button

The Ortho System™ Software has the same intended uses and technical characteristics as OrthoCAD iQ (K082207) from Cadent Inc. and Dolphin Imaging from Patterson Dental Supply (K110430):

Feature name	**3Shape Ortho System™**	**Primary predicate Cadent Inc. OrthoCAD iQ (K082207)**	**Reference predicate Patterson Dolphin Imaging (K110430)**
Supported anatomic areas	Maxilla	Maxilla	Maxilla
	Mandible	Mandible	Mandible
Intended use			
Managing patient and case base data	Yes	Yes	Yes
Collection of study material	Yes	Yes	Yes
Alignment of study material	Yes	Yes	Yes
Measuring study material	Yes	Yes	Yes
Analyzing study material	Yes	Yes	Yes
Treatment simulation	Yes	Yes	Yes
Virtual appliance design	Yes	Yes	Yes
Supported PC formats	Windows	Windows	Windows
Managing patient and case base data			
Creating, editing, deleting and copying patient data	Yes	Yes	Yes
Creating, editing, deleting and copying case data	Yes	Yes	Yes

Feature name	**3Shape** **Ortho System™**	**Primary predicate Cadent Inc. OrthoCAD iQ (K082207)**	**Reference predicate Patterson Dolphin Imaging (K110430)**
Collection of study material			
Surface scan for intra-oral scanner	Yes	Yes	Yes
Surface scan from STL file	Yes	Yes	Yes
CT image data	DICOM	No	DICOM
2D overlay	PNG, JPG, BMP	JPEG	PNG, JPG, BMP
Alignment of study material			
Aligning surface scan and CT image	Yes	No	Yes
Aligning cephalometric images	Yes	No	Yes
Alignment of 2D overlays (e.g. ideal arch)	Yes	No	Yes
Ability to check/adjust DICOM visibility	Yes	No	Yes
DICOM scan segmentation	No	No	Yes
Measuring study material			
2D measurement toolbox	Yes	Yes	Yes
3D measurement toolbox	Yes	Yes	Yes
Analyzing study material			
Arch shape	Yes	Yes	Yes
Wire length	Yes	Yes	Yes
Tooth width	Yes	Yes	Yes
Bolton	Yes	Yes	Yes
Space analysis	Yes	Yes	Yes
Overjet/overbite	Yes	Yes	Yes
Occlusion map	Yes	Yes	Yes
Treatment simulation			
2D & 3D simulation	Yes	Yes	Yes

Feature name	**3Shape** **Ortho System™**	**Primary predicate Cadent Inc. OrthoCAD iQ (K082207)**	**Reference predicate Patterson Dolphin Imaging (K110430)**
Virtual appliance design			
Orthodontic appliance search	Yes	Yes	Yes
Orthodontic appliance virtual preparation	Yes	Yes	Yes
Orthodontic appliance design	Yes	No	Yes
Orthodontic appliance export	Yes	Yes	Yes

Nonclinical Testing

Software, hardware, and integration verification and validation testing was performed in accordance with the FDA Guidance Document "Guidance for the Content of Premarket Submissions for Software Contained in Medical Devices" (Issued on May 11, 2005).

The validation suite includes validation of implemented mitigations related to device hazards identified in the risk management procedures.

All test results have been reviewed and approved, showing the Ortho System™ to be substantially equivalent to the predicates.

Clinical Testing

Clinical testing is not a requirement and has not been performed.

Conclusion

Based on a comparison of intended use, indications, principle of operations, features and technical data, and the test results, the Ortho System™ is found to be as safe and effective as the predicate devices. Intended use and performance is found to be substantially equivalent to the Predicate Devices.

Exhibit 5

ORAL SCANNING WITH 3SHAPE TRIOS® 3

FASTER IMPRESSION TAKING
Insane Speed Scanning with TRIOS

UNRIVALLED ACCURACY
Award Winning Accuracy

EASE OF USE
Easy to Use in Real Life Situations

ECONOMICAL
New Entry Level Option

The 3Shape TRIOS® 3 is the world's leading dental scanner. The new generation TRIOS® 3 makes scanning the mouth trouble-free and fast, with full arch scanning in as little as an incredible 10 seconds.

This new system is the 3rd generation TRIOS® with a three-in-one digital impression solution that allows you to complete a full arch scan in under 30 seconds.

The 3Shape TRIOS®3 enables you to be more precise and more efficient whilst providing greater comfort for your patients.

Oral Scanning With 3Shape TRIOS® 3

DIGITAL DENTISTRY EQUIPMENT

Blog Post - Why 3Shape?

DTS Chats to 3Shape Product Manager.

READ NOW

Recommended Materials

We recommend these for a digital workflow.

DISCOVER

Training & Support

We're here to support you with your new equipment.

MORE INFO

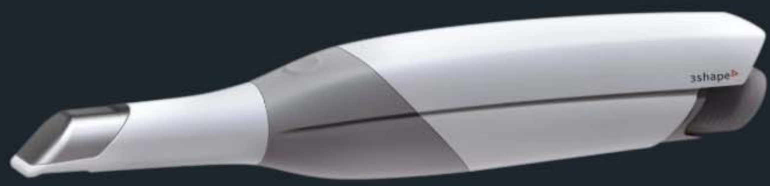
Related Documents | Related Videos

3Shape TRIOS® 3 Product Sheet

Exhibit 6

3shape REQUEST DEMO

3Shape TRIOS 3



Engage and excite your patients

Stay ahead of the game. Combine award-winning TRIOS® scan technology with next-level patient communication tools and a broad range of in-house production possibilities to help you Go Beyond SCANNING®. The 3Shape TRIOS® 3 intraoral scanner has it all.

GO BEYOND SCANNING

Superior technology and apps

TRIOS 3 offers so much more than just a digital impression. It provides award-winning wireless scan technology and the unrivalled open TRIOS ecosystem with total integration to your preferred partners for all indications. Combine this with a software suite and start exciting patients about proposed treatment, reduce chair time, and offer new treatment opportunities.

BENEFITS

Wireless innovation

Scan unrestricted by wires, optimizing comfort for both you and your patients and making scanning easier.

Excitement apps

Excite patients by bringing treatment outcomes to life, and advance case acceptance like never before!

Studio apps

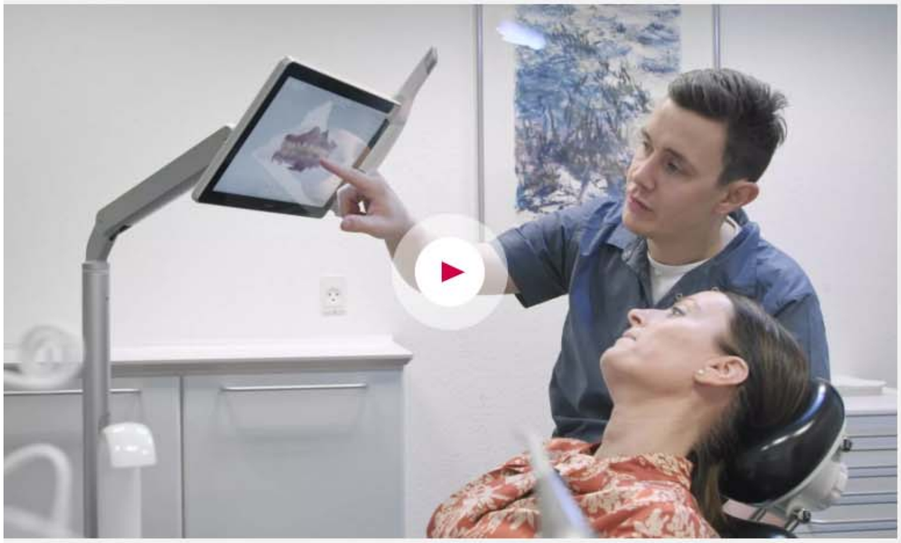
Grow your business with a choice of software solutions to design and produce in-house and start offering same-day dentistry.

WHAT YOU SHOULD KNOW ABOUT QUALITY

We've collected and summarized clinical studies comparing intraoral scanners and conventional workflows, and put together an information-packed webinar on the stages of going digital for you. Get access to resources like these now!

LEARN MORE

TRIOS MOVE



Bring scans and expected outcomes up-close

Excite your patients by displaying their scans and proposed treatment designs up close. With the 3Shape TRIOS® MOVE® and MOVE+, you can always position the screen and scanner in the right place for optimal viewing, patient comfort and ergonomics.

EXPLORE

EXCITEMENT APPS

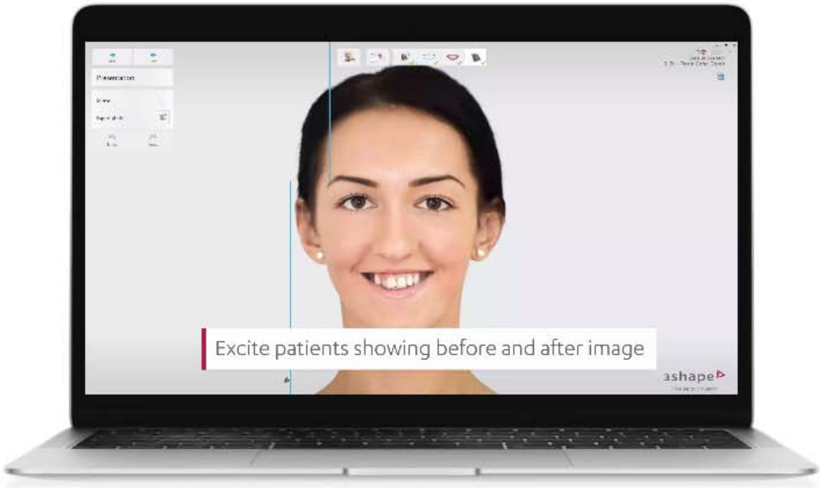
TRIOS Smile Design

TRIOS Treatment Simulator

TRIOS Patient Monitoring

Show patients their future smiles

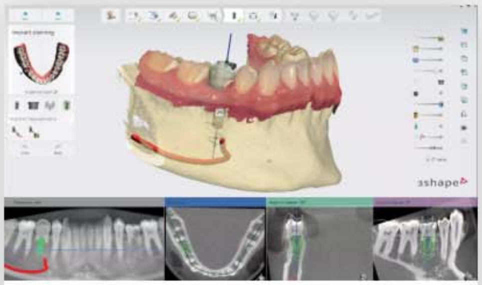
Simply take a photo of your patient's face, easily design their new beautiful smile in minutes and share it with your patient. Smile Design lets you send smile designs directly to your patient's phone so they can share with friends and family.



IN-HOUSE DESIGN AND PRODUCTION

Gain profitable in-house production options with an array of TRIOS software, accessories and integrations to grow your business and offer attractive same-day dentistry services.

TRIOS Design Studio®



Implant Studio®

Plan, design and print custom surgical guides and temporary screw-retained crowns* in one workflow.

EXPLORE

Splint Studio®*

WANT MORE?

If you want to Go Beyond TREATMENT with our most advanced intraoral scanner ever, explore the 3Shape TRIOS 4 with caries detection aid* and patient monitoring tools.

TRIOS 3 Basic | TRIOS 3 | TRIOS 4

Go Beyond ANALOG

- Superior scanning technology
- Unrivalled open system

Go Beyond SCANNING

- Superior scanning technology
- Unrivalled open system
- Patient excitement apps
- In-house design and production

Go Beyond TREATMENT

- Superior scanning technology
- Unrivalled open system
- Patient excitement apps
- In-house design and production
- Caries diagnostic aid and monitoring tools*
- Preventative care possibilities

CALCULATE SAVINGS

DOWNLOAD DETAILS

Download brochure

English

DOWNLOAD PDF

Go Beyond SCANNING

Do your patients and your business a favor.

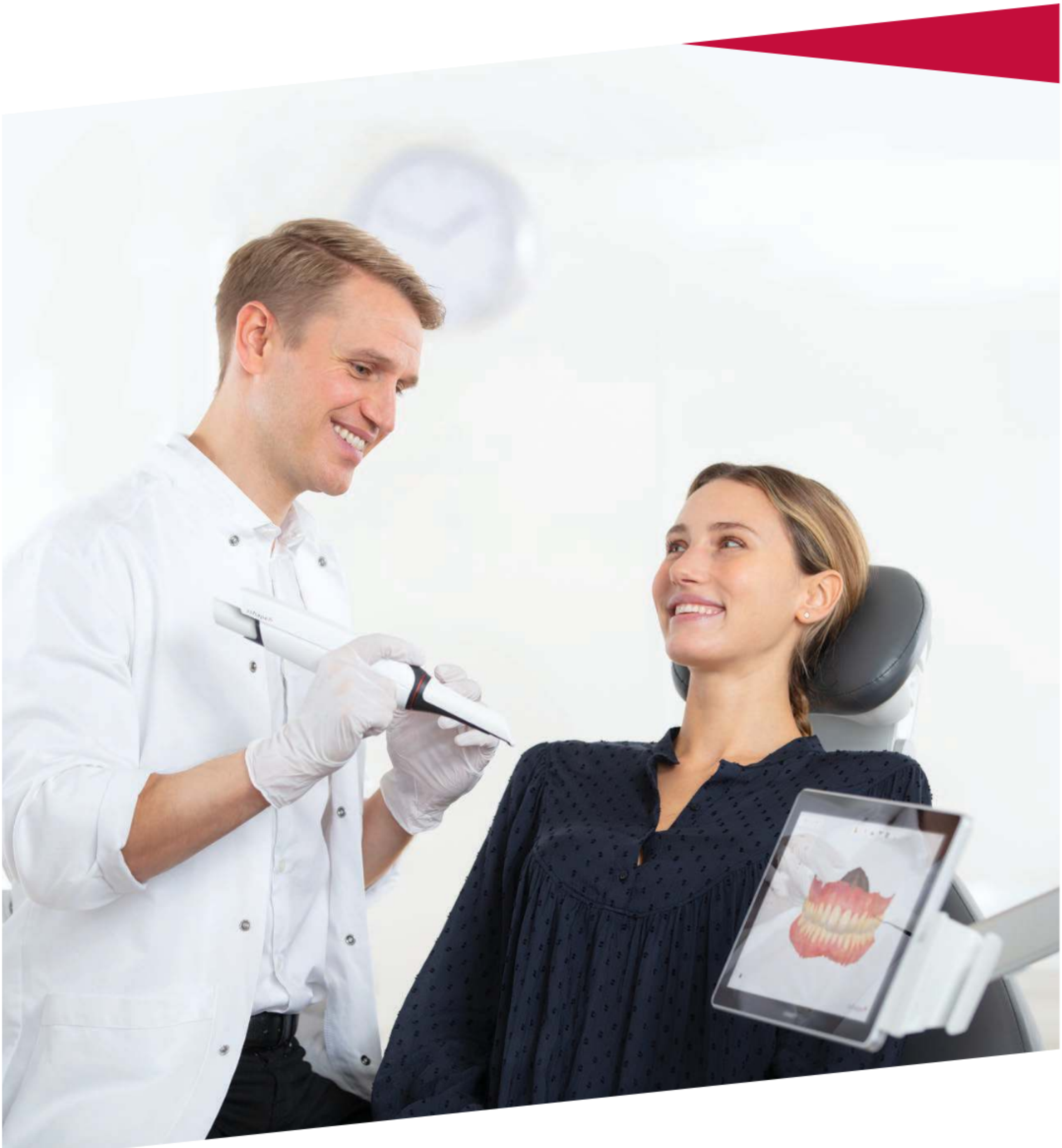
DO MORE

*TRIOS Diagnostic Aid software, Splint Studio and Abutment Design for design of screw retained crowns are not cleared by the FDA for clinical use in the US.

Contact your reseller regarding availability of 3Shape products in your region or country.

3Shape TRIOS

Go Beyond on your digital journey

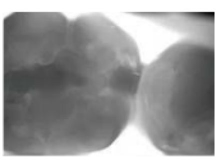


3shape

Be equipped for success with NEW 3Shape TRIOS innovation

3Shape TRIOS® 4

The most powerful 3Shape intraoral scanner to date!



Caries diagnostic aid*

The world's first intraoral scanner with digital detection of possible surface and interproximal caries** without the need for an additional scanning device.

Smart tips

New generation of tips with instant-heat technology so you are scan-ready in seconds, and enabling 30% additional battery life. Plus a dedicated tip to aid the detection of interproximal caries.**

3Shape TRIOS 3 Basic

The entry-level intraoral scanning solution

> Core award-winning TRIOS scanning technology.
> Simple 'scan and send-to' workflow.

Go Beyond with 3Shape TRIOS

Whether you are a digital newcomer wanting a scan-only solution or a fully-digital practice ready to embrace pioneering technology to facilitate your preventative care goals, TRIOS always enables you to do more and Go Beyond in your delivery of superior patient care.

Go Beyond ANALOG >

> Superior scanning technology
> Unrivalled ecosystem

Go Beyond SCANNING >

> Patient excitement apps
> In-house production

Go Beyond TREATMENT >

> Caries diagnostic aid* and monitoring tools
> Preventive care possibilities

CELLERANT
BEST OF CLASS
TECHNOLOGY AWARD
6 TIME WINNER

It all starts with superior scanning technology

3Shape TRIOS® – more than just a digital impression!

Wireless innovation for enhanced comfort and ease

The world's first wireless scanner option enables you to scan unrestricted by wires, optimizing comfort for both you and your patients, and making scanning easier.

TRIOS Patient Specific Motion to perfect your restorations

Record a series of different bite positions and highlight occlusal contacts for dynamic patient specific articulation.

Realistic colors and shade measurement for patient engagement

Create high-quality digital impressions in lifelike colors and apply shade measurement to evaluate treatment and activate quality dialogue with patients.

Strong research evidence for excellent TRIOS accuracy

18 independent studies report statistically higher accuracy for TRIOS compared with conventional impressions and/or impressions made with other major intraoral scanners for full arch, single unit and multi-unit restorations.[1]

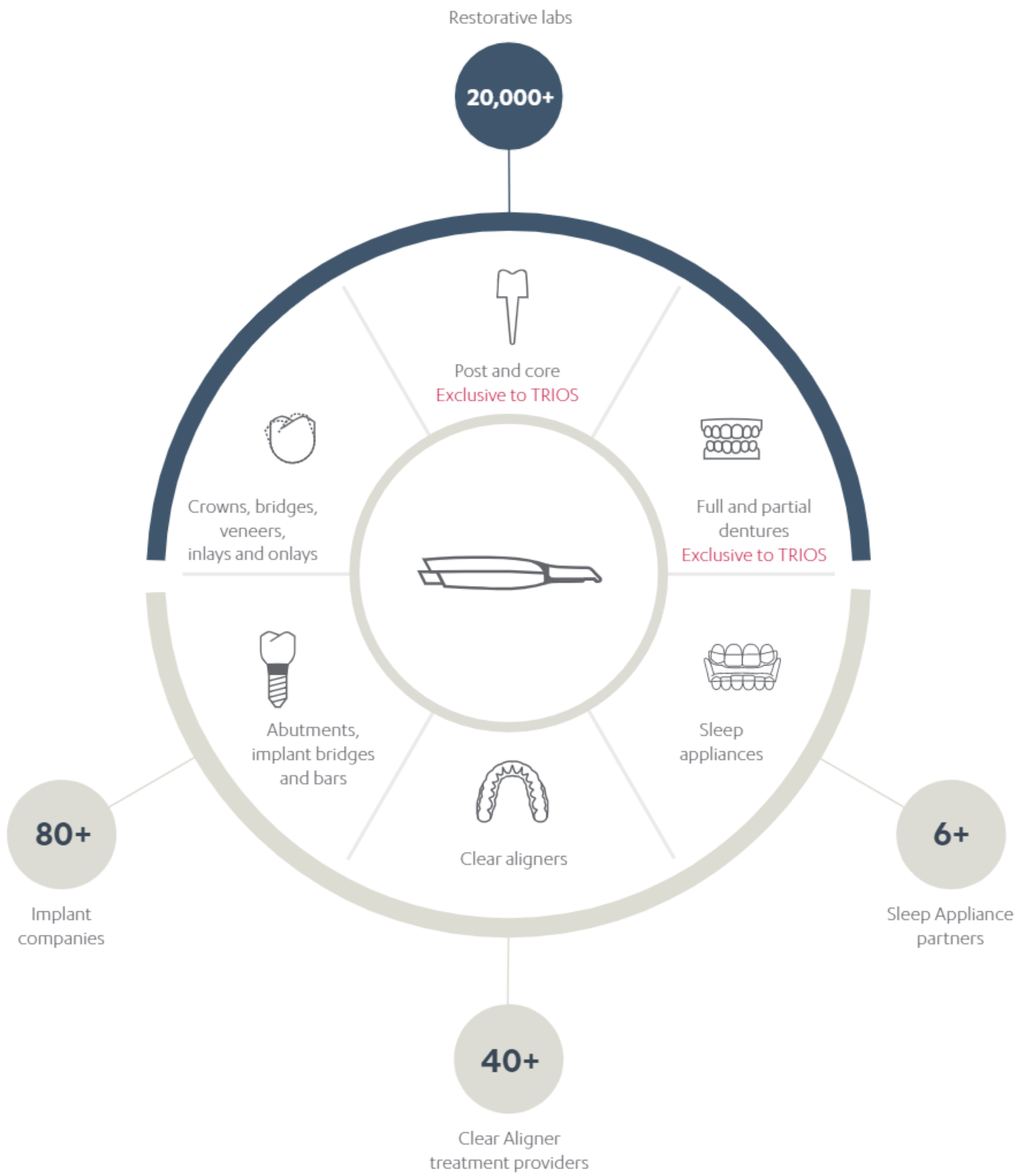
NEW!

AI scan technology for simplified scanning

Removes unnecessary soft tissue as you scan to make scanning easier.

Access an unrivalled ecosystem

Empower your practice with the comprehensive, ever-expanding and open TRIOS® ecosystem. With total integration to your preferred partners for all indications, you can secure the best and most cost-effective options for your business.



"Scanning with TRIOS enables me to perform virtually all indications, providing workflows that seamlessly connect to the most competitive partners."

Dr. Christopher Ho
Sydney, Australia

Excite your patients and advance case acceptance

Bring expected treatment outcomes to life with 3Shape TRIOS® MOVE and TRIOS excitement apps.

Gain next-level patient engagement and great ergonomics with TRIOS MOVE

Excite your patients by displaying their scans and treatment designs up close, and enjoy the ease of always being able to position the setup in the right place for optimal comfort.

Give patients remote access to their digital data to stimulate treatment acceptance

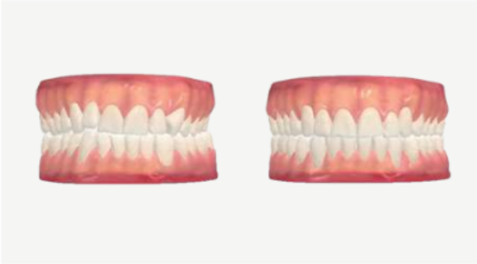
Allow patients to view their dynamic treatment proposals on their mobile device using the My 3Shape app, and encourage them to share and discuss treatment options with family and friends.

Show patients their future smile with TRIOS Smile Design

Take a photo of your patient's face and design their beautiful new smile in just minutes. Share the photorealistic results with your patient to align expectations and stimulate treatment acceptance.

Grow orthodontic treatments with TRIOS Treatment Simulator

Scan your patient and show their present dentition compared to the expected results of orthodontic treatment to gain greater case approval.

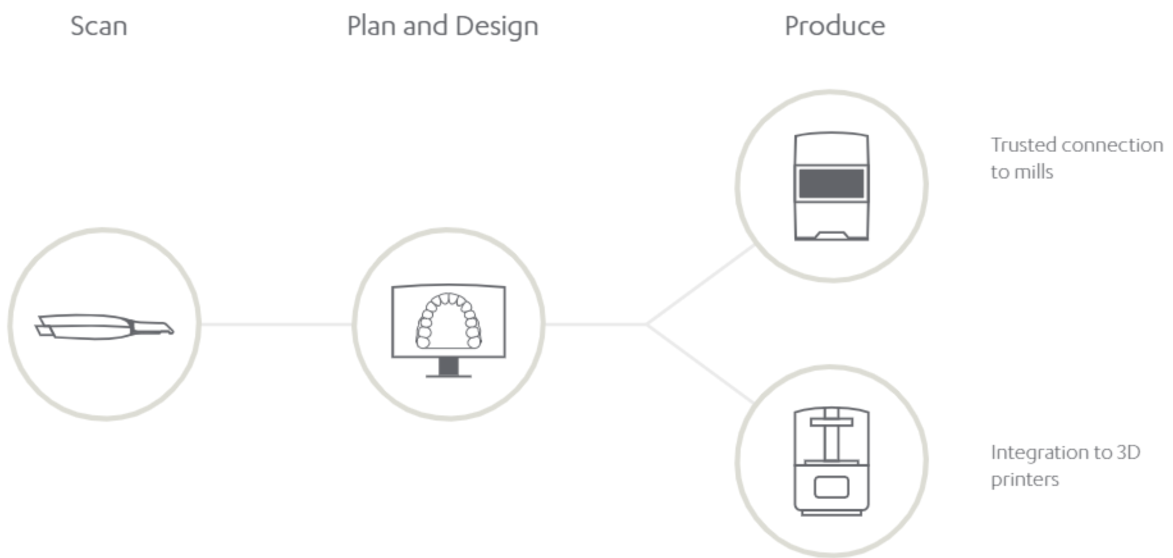


"To be able to see what my smile could be, was very emotional. Now I'm at the point where it looks exactly like it did in TRIOS Smile Design. I can't believe it!"

Samantha Morra, Patient
New York, USA

Grow your business by producing in-house with TRIOS Studio apps

3Shape's open system includes TRIOS® Studio apps with seamless integration, trusted connections to leading third-party mills and compatibility with all 3D printers. This enables you to do more, gain profitable in-house production options and exceed patient expectations.



"Offering less invasive surgery and same-day dentistry allows me to provide great patient treatment experience and gain greater control."

Dr. Simon Kold
Herning, Denmark

TRIOS Design Studio

Design and produce a broad range of restorations, including standard and screw-retained crowns***, inlays, veneers and three-unit bridges.

Implant Studio

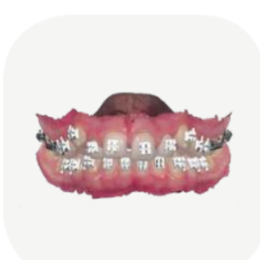
Plan implant positions, and design and manufacture custom surgical guides and temporary screw-retained crowns*** in one workflow.

Splint Studio

Design and produce splints, night guards, protectors and similar dental appliances with a simple, fast and intuitive workflow.***

Clear Aligner Studio

Access a complete solution that enables you to design and produce clear aligners in your clinic, with a high return on investment potential.

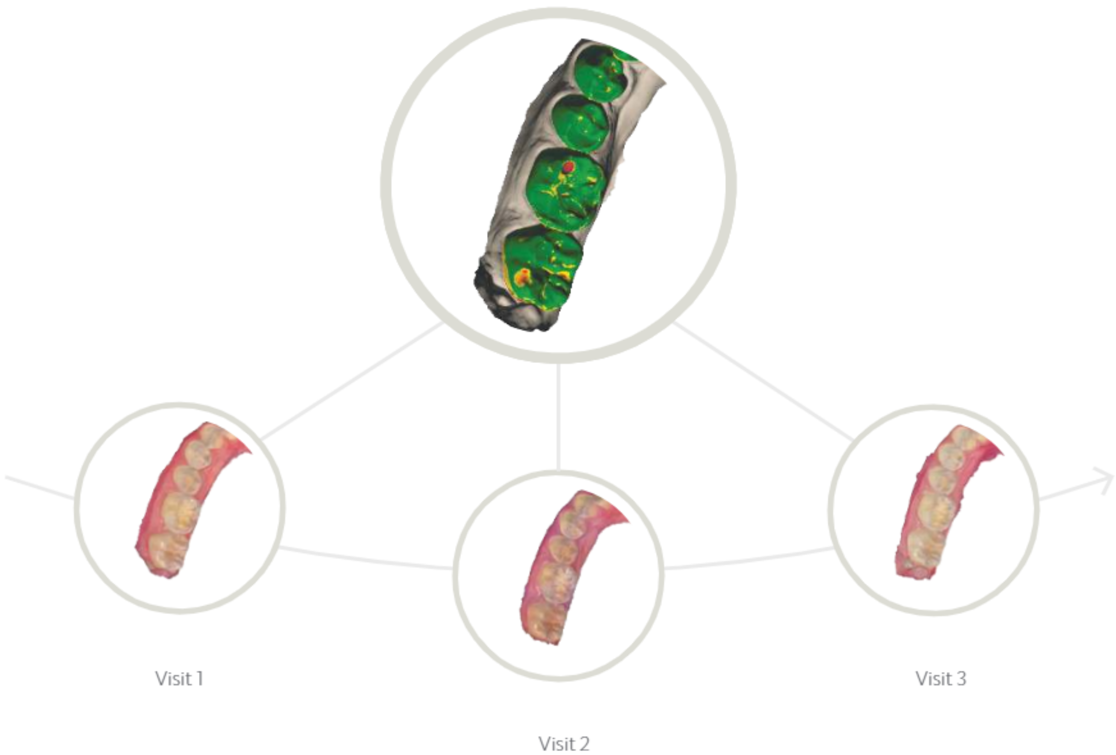


Indirect Bonding Studio

Plan bracket placement, and design and produce transfer media for indirect bonding.

Enable preventive care with caries diagnostic aid and monitoring tools

Compare via
TRIOS Patient Monitoring

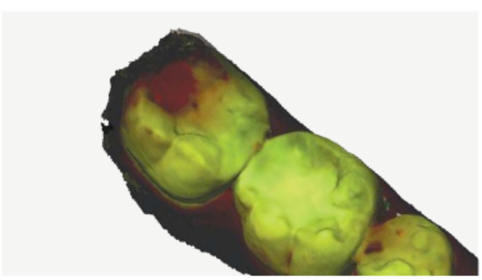


TRIOS® Patient Monitoring for preventive insights

Scan every patient every time to accurately track changes in teeth and identify dental conditions sooner. Share visual monitoring information with patients to advance their understanding of issues and the need for treatment.

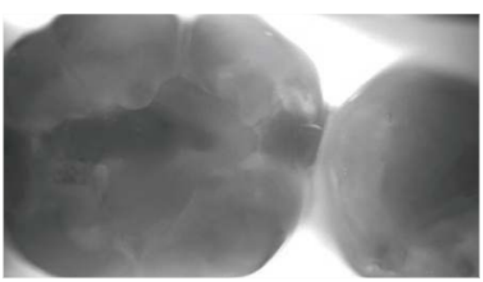
NEW WITH TRIOS 4!

Caries diagnostic aid* for early detection and timely intervention of suspected caries



Surface caries

Use TRIOS 4's built-in fluorescent technology and identify possible caries by overlaying the standard 3D TRIOS scan with new color-coded data. Compare to earlier scans to visually identify potential changes.



Interproximal caries**

Without radiation, the new TRIOS 4 transillumination smart tip aids the identification of possible interproximal caries** undetectable to the eye. Show the results to your patients to help them understand the need for any recommended treatment.

"Creating an aid for caries detection without radiation has been an elusive goal in dentistry – this is a ground-breaking achievement. Once again, 3Shape TRIOS redefines scanning!"

Dr. Jonathan L. Ferencz
New York, USA

A fit for every practice

Configure and equip your TRIOS® according to your needs and budget.

1. Choose your scanner

TRIOS 4

TRIOS 3
Available in pen and handle grips

TRIOS 3 Basic
Available in wired pen version only

2. Choose your connection

Wireless
Option for TRIOS 4 and TRIOS 3

Wired

3. Choose your setup

MOVE

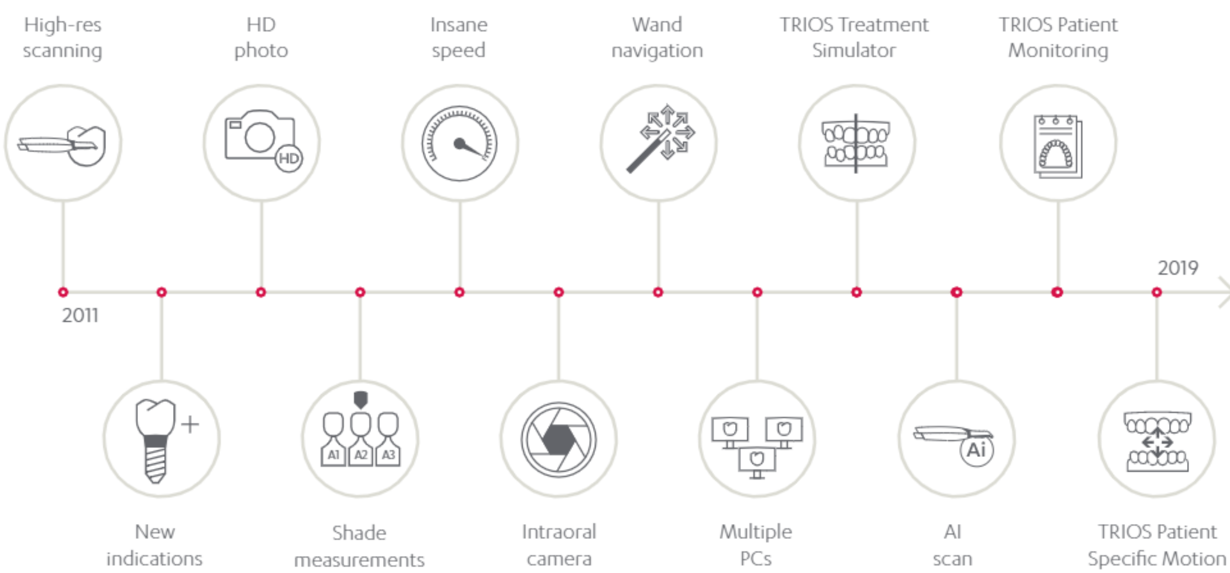
CART
Available with TRIOS 3 Basic and TRIOS 3

POD

		TRIOS 4	TRIOS 3	TRIOS 3 Basic
Scanner generation		4th	3rd	3rd
Scanner features	Wireless	✓	✓	N/A
	AI scan	✓	✓	✓
	3Shape accuracy	✓	✓	✓
	Real colors and shade measurement	✓	✓	✓
	Smart tips	✓	N/A	N/A
	Caries diagnostic aid*	✓	N/A	N/A
Software and apps	TRIOS Patient Monitoring	✓	✓	Upgrade to TRIOS 3
	TRIOS Treatment Simulator	✓	✓	Upgrade to TRIOS 3
	TRIOS Smile Design	✓	✓	Upgrade to TRIOS 3
	TRIOS Patient Specific Motion	✓	✓	Upgrade to TRIOS 3
	In-house apps	Add-on option	Add-on option	Add-on option

Future-proof your TRIOS with CliniCare

Get upgrades, online support, training and more in one simple subscription that ensures you are always equipped for peak clinical performance.



Share and learn with the 3Shape Community

Connect and network with your 3Shape digital peers around the world, access training materials, showcase your best work and learn how to get the most out of your TRIOS solution. Get started today at community.3shape.com.

References
(1) 18 in vivo and in vitro studies (between 2015 and 2018). Data on file.
* Caries diagnostic aid not cleared by the FDA for clinical use in the US.
** Detection aid of possible interproximal caries using infrared scans coming soon.
*** Splint Studio and abutment design for screw-retained crowns not cleared by the FDA for clinical use in the US.

About 3Shape

3Shape is changing dentistry together with dental professionals across the world by developing innovations that provide superior dental care for patients. Our portfolio of 3D scanners and CAD/CAM software solutions for the dental industry includes the multiple award-winning 3Shape TRIOS® intraoral scanner, the 3Shape X1® CBCT scanner, as well as market-leading scanning and design software solutions for both dental practices and labs. Two graduate students founded 3Shape in Denmark's capital in the year 2000. Today, 3Shape employees serve customers in over 100 countries from 3Shape offices around the world. 3Shape's products and innovations continue to challenge traditional methods, enabling dental professionals to treat more patients more effectively.

Why 3Shape TRIOS?

Give a great treatment experience

Excite patients by bringing digital impressions and treatments to life

Get more open options

Choose lab or in-house production, with access to an unrivalled ecosystem

Grow your practice

Advance case acceptance, expand your offer and boost profitability

Contact your reseller regarding availability
of 3Shape products in your region

82602691 3Shape TRIOS 2019 Broch USA

3shape

Exhibit 7

SEE 3Shape TRIOS 3 WIRELESS INSANE SPEED IN ACTION

3Shape

Subscribe 12.9K

122,002 views

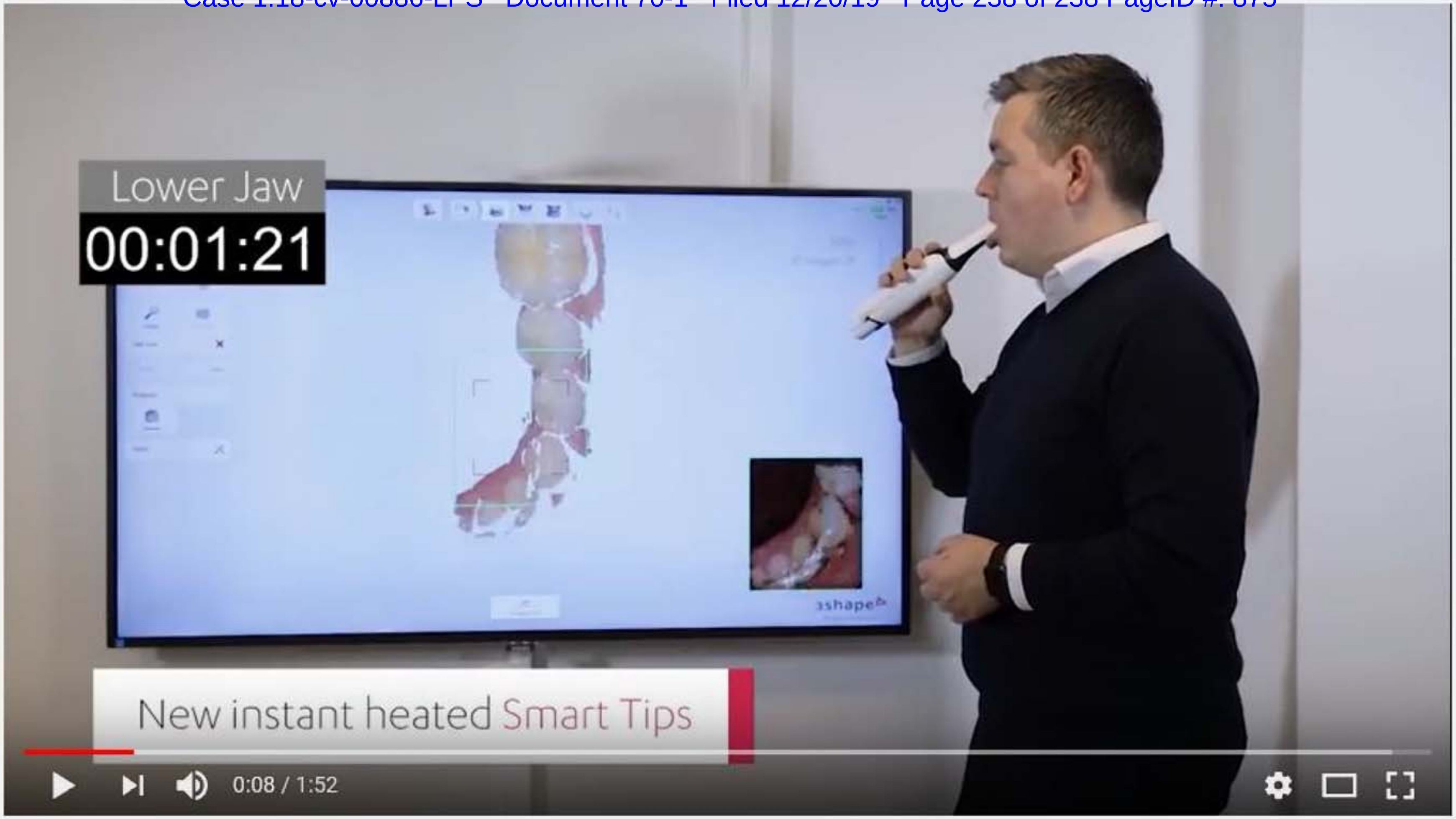
Add to Share ••• More 319 17

Published on Mar 21, 2017

https://www.3shape.com/products/trios...

Wireless scanning is insane fast! - Really fast - See here!

Exhibit 8



3Shape's MORTEN RYDE DEMONSTRATES THE NEW 3Shape TRIOS 4

3Shape

Subscribe 12.9K

12,725 views

Add to Share ••• More 86 2

Published on Mar 12, 2019

JUST LAUNCHED AT IDS 2019
TRIOS 4 is the world's first intra-oral scanner with detection of both surface and interproximal caries. Go beyond TREATMENT with TRIOS 4
Read more about TRIOS 4: http://ow.ly/jcOX30o0OJb